# *Hydrogeology*

# *of the*

# *Waipara Alluvial Basin*

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***Volume One: Thesis***

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## Abstract

The Waipara alluvial basin, located 50 kilometres north of Christchurch on the South Island of New Zealand is experiencing rapid transformation in land use from pastoral farming to horticulture. In the last five years the use of the groundwater resources has increased significantly. Knowledge is lacking about the availability and sustainability of the groundwater resources.

Groundwater resources can be found throughout the basin in the Quaternary Canterbury and Teviotdale Gravels, and the late Pliocene/Early Pleistocene Kowai Formation. The hydrogeological system can be described as a complex network of discrete, lithologically and hydraulically heterogeneous and aniosotropic semi-permeable to permeable channels. The physical and hydraulic nature of the aquifers (or water-bearing units) makes identification and characterisation of the resources difficult. However, the resources can be distinguished in terms of the observed hydrogeologic properties (i.e. lithology, yield, transmissivity, and chemistry).

Chemical and isotope sampling indicate that recharge to the basin aquifers is occurring through the uplifted and fractured Tertiary sequences formed along the eastern and western margins of the basin, and through infiltration of local rainfall in the unconfined and semi-confined portions of the aquifer. Groundwater residence times are long (20-40+ years). Long residence times, slow recharge, and low hydraulic conductivity suggests that if the groundwater resources are not properly monitored and managed, there is great potential for 'mining' the resource(s), or in other words for depleting the resource faster than it can be recharged.

Long term monitoring and management strategies have been recommended for future work to help gain more knowledge and understanding of the Waipara hydrogeological system, and ensure sustainability for future development.

## Acknowledgements

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# CHAPTER ONE
# INTRODUCTION

## 1.1 Project Background

The Waipara basin located in North Canterbury, approximately 55 km north of Christchurch on the east coast of the South Island of New Zealand (Figure 1.1), is experiencing a rapid transformation in both land and water use. Farms once used for pastoral farming, are being subdivided into smaller blocks, and sold primarily for the growth of olives and grapes. The horticultural and viticultural type farming has resulted in a significant increase in the demand for groundwater. Knowledge is lacking about the regional groundwater resource, particularly as to what depth(s) it might be found, and whether the presently used resources are capable of sustaining future development. These questions initiated the formation of the 'Water for Waipara' action group in August 1998, and ultimately the undertaking of this thesis to provide answers.

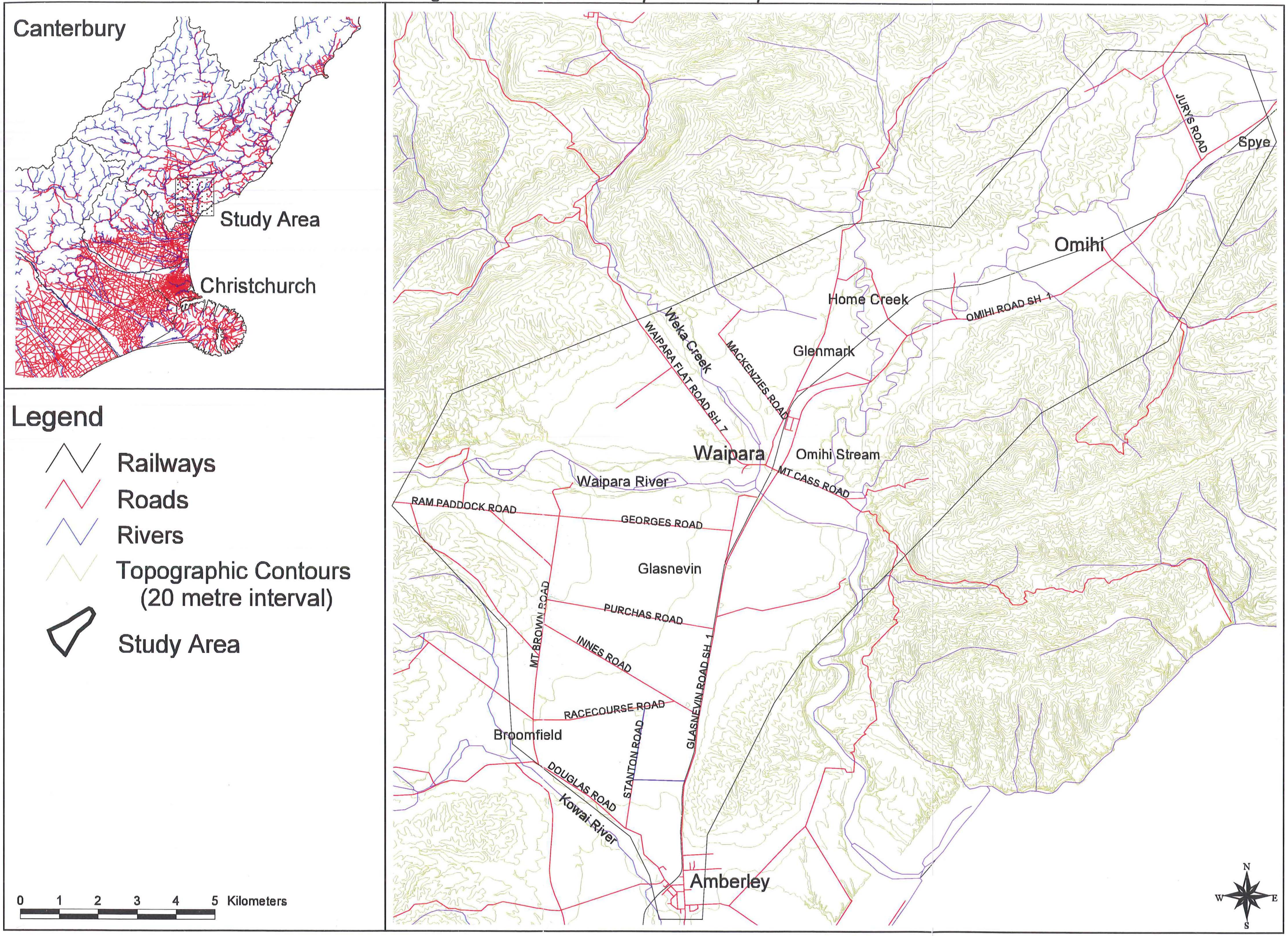
## 1.2 Objectives

The primary objective of this investigation is to provide a comprehensive evaluation of the groundwater resources in the region, and to generate a conceptual model of the groundwater system(s). Consequent objectives include: collation of information about the groundwater resources of the Waipara Basin, identification of the hydrogeological properties of the aquifers and sources of groundwater recharge, development of a long-term monitoring programme, and to suggest future investigation strategies for effective management of the groundwater resources. A secondary objective is to assess the merits of using geophysical techniques for locating and mapping aquifers. Ultimately, the above objectives will enable more efficient use, and management of the resources by Environment Canterbury, which aims to protect the resource and current users by ensuring its sustainability.

## 1.3 Study Area

The area under investigation encompasses the region between the northern limit of the Amberley township (Douglas Rd) to Spye and Omihi (Figure 1.1). The study area is approximately 120 $km^2$, and is for the most part confined to the valley floor, as this is the

*Figure 1.1 - Location Map of the Waipara Alluvial Basin*



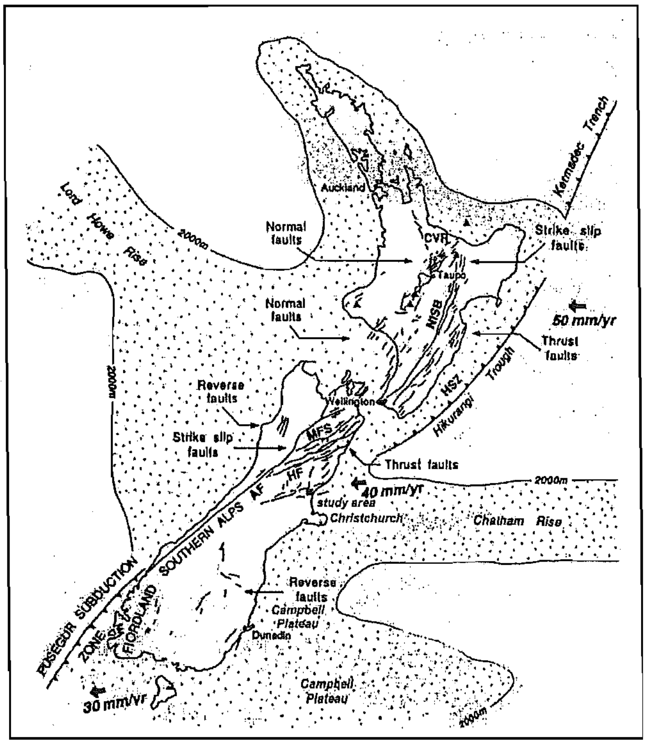
area that is being developed for horticultural and vitricultural farming. The largest surface water resource is the Waipara River, a perennial river that flows across the centre of the valley from the western ranges to the coast. Other significant surface waters in the valley include the Omihi Stream, Home Creek and Weka Stream, all of which run dry along segments of their course during the summer.

## 1.4 Regional Geological Setting

### 1.4.1 Tectonic Setting

New Zealand is located on an obliquely convergent plate boundary between the Pacific and Australian plates (Figure 1.2). Plate convergence along the northeast coast of the South Island has caused uplift and buckling of the overriding Australian Plate, resulting in the formation of the Southern Alps. The two major structures accommodating the stress produced along this boundary are the Alpine Fault and the Marlborough Fault System (MFS). The Alpine Fault is a major strike-slip fault extending across the South Island, and the MFS is a zone of right-lateral strike-slip transfer faults, located northeast of the Alpine Fault. The study area is located at the south-eastern margin of the MFS (Figure 1.2). The proximity of the study area to the MFS has resulted in the development of a belt of northeast trending folds and reverse/ thrust faults, which help to accommodate some of the stress produced along the plate boundary.

***Figure 1.2 – New Zealand Plate Boundary***




(Pettinga and Armstong, 1998)

### 1.4.2 Waipara Basin

The Waipara basin is a southeast plunging synclinal structure formed by pre-Cretaceous basement and Tertiary sedimentary rocks, infilled by Quaternary alluvium (Figure 1.3a and 1.3b, back pocket). The basin is bound to the west by basement rock, which has been uplifted by the Grey Fault. North of the Grey Block, lateral movement along the Boby's Creek Fault has offset the western limb of the syncline. To the east, the Waipara basin is bounded by the Omihi Fault, a concealed-segmented westward verging thrust fault. East of the Omihi Fault, three NE trending anticlines (the Black, Cass and Kate anticlines) have developed in an *en echelon* manner, and form the eastern margin of the basin (Figure 1.4). Other structural features of the Waipara region are gently plunging anticline-syncline pairs, many of which are asymmetric in form and bounded by a fault on one or more sides (Nicol, 1991).

***Figure 1.4 –Cass Anticline(foreground right) and Black Anticline (background right) looking NE from Broomfield***

Rocks of the Waipara basin were deposited in three periods, separated and accompanied by periods of tectonic activity. The oldest rocks are compacted sandstones and mudstones (greywacke and argillite) intermixed with sparse conglomerates and volcanics, which were formed during the Triassic to Jurassic periods (Wilson, 1963). The first and second events of deposition are separated by a period of metamorphism (Hokonui Orogeny), and several periods of erosion, which are marked by minor unconformities in the rock record (Wilson, 1963,1983). Folding and uplift during the Hokonui Orogeny contributed to the formation of the Waipara syncline by the Early Cretaceous. The second period of deposition occurred during the mid-Cretaceous to Tertiary and resulted in the accumulation of a marine transgression-regression sequence. The third period of deposition included the accumulation of thick sequences of fluvial gravel, derived from erosion of uplifting mountains (Kaikoura Orogeny) in the late Pliocene-early Pleistocene. The Kaikoura Orogeny continues to the present day, and has resulted in deformation and tilting of the early Pleistocene alluvial deposits, and the formation of the Canterbury Plains.

### 1.4.3 Geomophology

Along the eastern margin of the basin, the Cass and Black anticlines emerge rather abruptly from the valley floor, reflecting the presence of the concealed Omihi Fault. The topographic relief is dominated by a series of northeast trending anticline-syncline structures composed of pre-Cretaceous basement and Tertiary sediments. The region is dominated by gently rolling hills with dissected by subparallel gullies that exhibit a subtrellis and dendritic drainage pattern. Uplifted tilted terraces occur to the west of the basin by the Deans, and to the east along the base of Mt. Cass.

The primary geomorphic surface is a broad, flat aggradational surface (Canterbury Surface) located along the present day courses of the Waipara River, the Weka Creek, Omihi Stream and Home Creek (Wilson, 1955,1963), (Figure 1.5, back pocket). North of the Waipara River, the broad Canterbury-Omihi geomorphic surface has been degraded by the Weka Creek, Home Creek and Omihi Stream giving rise to several flights of terraces in a complex arrangement (Figure 1.6). All surfaces lower than the Canterbury Surface are degradational surfaces.

### 1.4.4 Soils, Climate and Vegetation

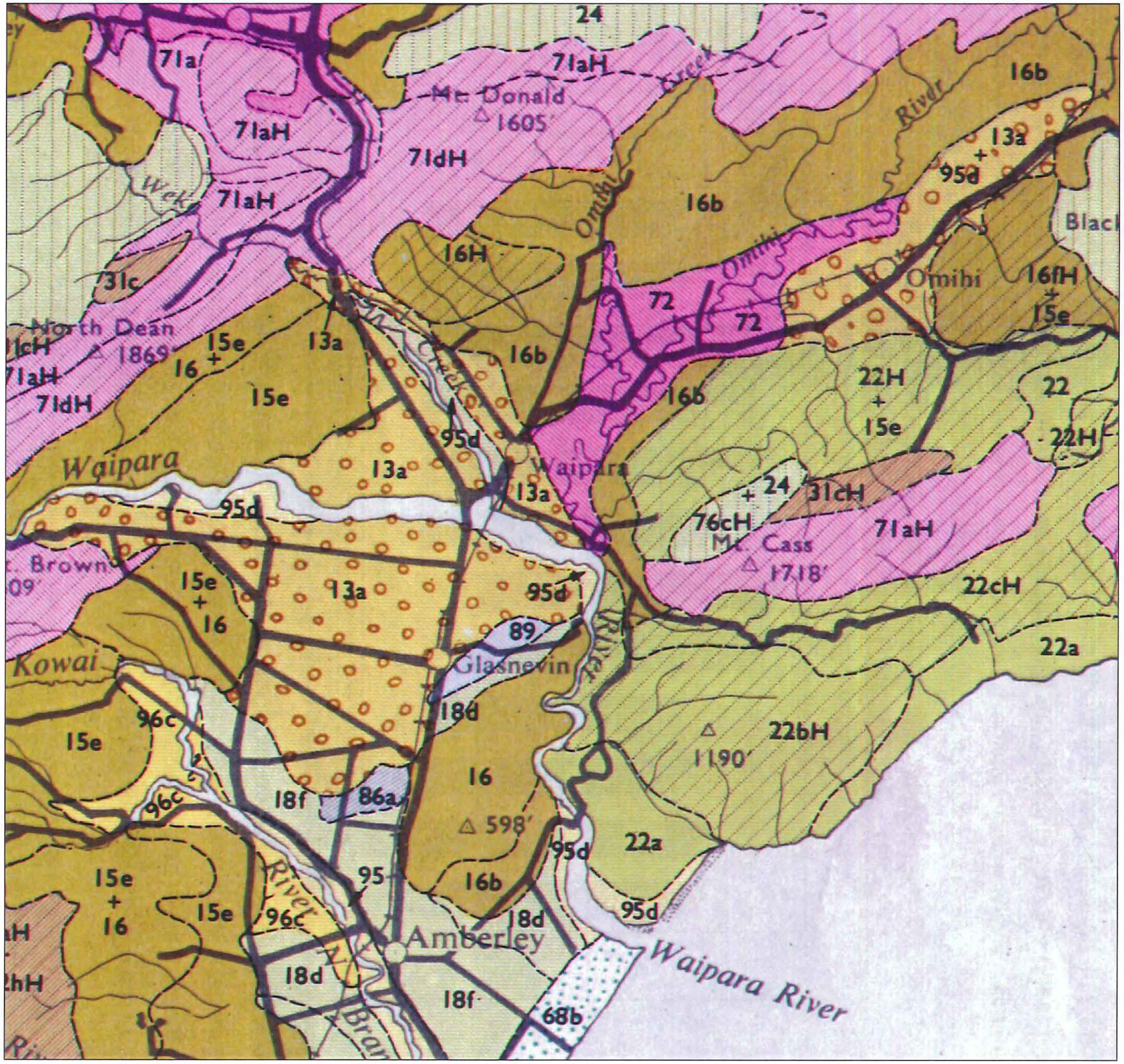
#### *1.4.4.1 Soils*

The most widespread soils in the valley are silty and sandy loams, which range from 20-30 cm in thickness and underlie 20 cm of topsoil (Figure 1.7). Beneath the loamy soils is a clay pan layer, which may impede drainage and root penetration. The soil types

***Figure 1.6– Canterbury Aggradation Surface and Alluvial Degradation Terraces of the Waipara River. Looking East to Mt. Cass***

(Photo: J. Weeber)

***Figure 1.7- Soil Map of the Waipara Valley (Modified from NZMS Soils Map - Sheet 6, 1963)***




**LEGEND**

YELLOW GREY EARTHS
*Subhygrous yellow brown shallow and stony soils*
- 13a Glasnevin (terraces and fans)
- 15e Waipara (rolling lands and hills)
- 16/16H Amberley
- 16b Glenmark (rolling lands and hills)
- 16fH Tipapa

*Dry-hygrous yellow brown shallow and stony soils*
- 18d Domett (terrace lands and fans)
- 18f Wakanui (terrace lands and fans)
- 22/22H Cheviot
- 22a Motunau (rolling lands and hills)
- 22bH Stonyhurst (rolling lands and hills)
- 22cH Glendhu
- 24 Haldon (Steeplands and hills)

YELLOW GREY to YELLOW BROWN EARTHS INTERGRADE
*Hygrous*
- 31c / 31cH Onepunga (rolling lands and hills)

YELLOW BROWN SANDS
*Sub-hygrous to hygrous*
- 68b Taumutu

RENDIZNA AND RELATED SOILS
*Sub-hygrous to hygrous*
- 71a/71aH Waikari (rolling lands and hills)
- 71dH Hui Hui (rolling lands and hills)

*Hygrous*
- 72 Omihi (terraces and fans)

BROWN GRANULAR LOAMS AND CLAYS
*Hygrous*
- 76cH Cookson-Waikari (rolling lands and hills)

ORGANIC SOILS
- 86 Waimairi (lowlands)

GLEY SOILS
- 89 Temuka

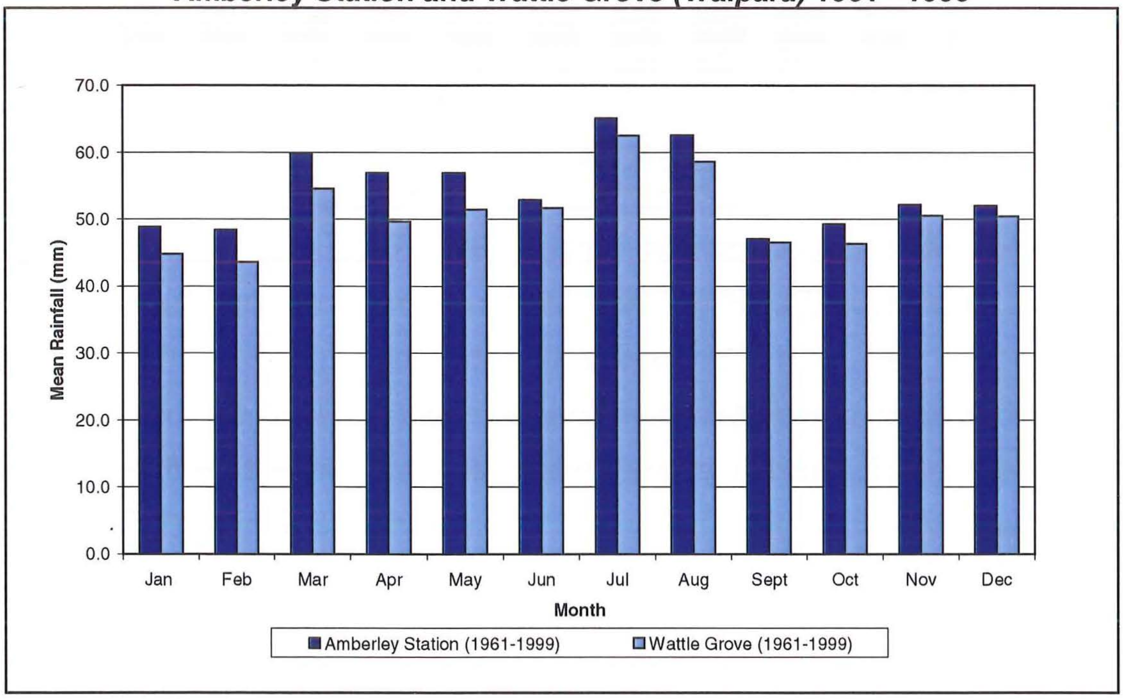
RECENT SOILS (intergrades to adjacent soils)
- 95 Waimakariri (flood plains and young fans; derived from alluvium)
- 95d Willowbridge (flood plains and young fans; derived from alluvium)
- 95d Mayfield

throughout the valley are extremely variable, changing from one paddock to the next. Soils located between Douglas Road, State Highway 1 and Stanton Road are typically high in clay content and tend to become super saturated in the winter months. Conversely, soils located between Innes and Georges and McKenzies Road in the Waipara Township, Glenmark and Omihi, are yellow-brown dry hydrous soils, particularly along the margins of the valley where tilted gravel terraces rest at the base of the anticlines.

### *1.4.4.2 Climate*

The Waipara region is one of the driest places in Canterbury with a mean annual rainfall less than 700 mm/yr. Rain is uniformly spread throughout the year, although July and August tend to be the wettest months, while January and February are the driest as shown in Figure 1.8 (New Zealand Meteorological Service, 1998; NIWA Climate Database, 1999).

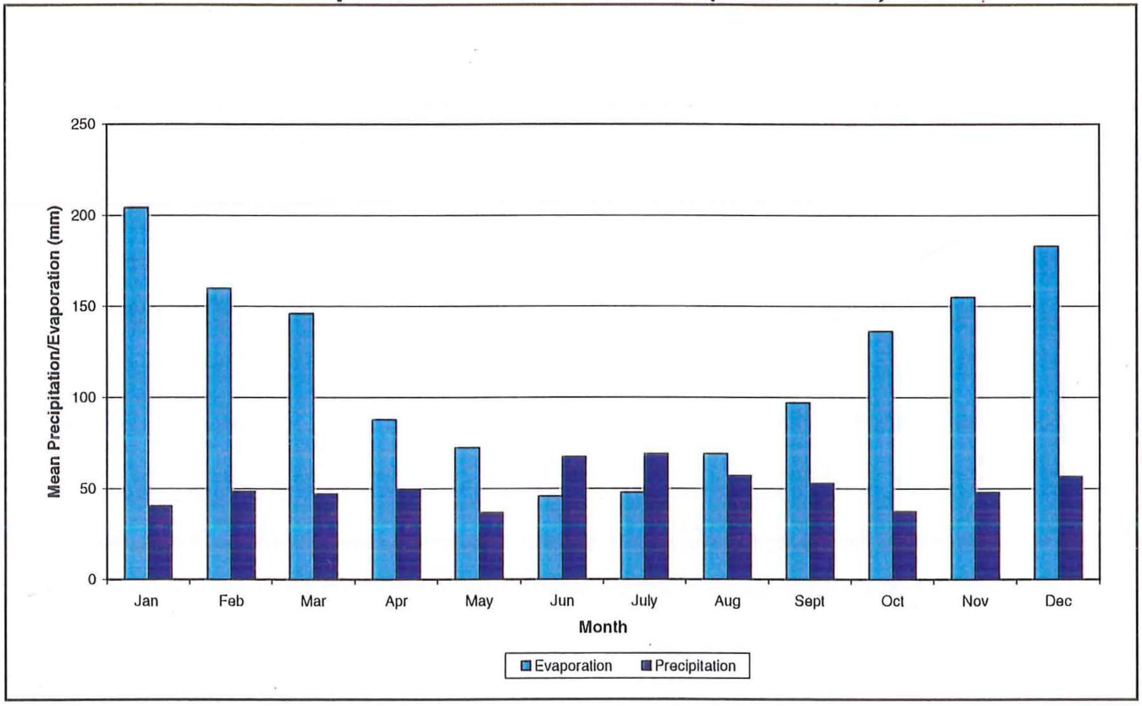
***Figure 1.8 – Comparison of Mean Monthly Precipitation for Amberley Station and Wattle Grove (Waipara) 1961 - 1999***




Rainfall is predominantly produced by southerly fronts from both the southwest and southeast during the winter months. Rainfall during the summer months is significantly lower as hot, dry northwest winds prevail. In addition, evaporation increases significantly in the summer months thereby limiting the rain infiltration to the water-table (Figure 1.9).

The climatic effects vary locally with the southern part of the valley experiencing more rainfall, and frosts with predominating easterly winds than the northern part, which is sheltered by the Cass and Black Anticlines. A lack of water for stock is often a concern for most farmers during the summer months, and water storage facilities are an essential component of farming in the area.

***Figure 1.9 – Evaporation vs. Precipitation Waipara West Climate Station (1990 – 1999)***




During the last three years (1997-2000), atypical climatic conditions have prevailed with the El Niño- La Niña phenomena. In 1997-1999, El Niño brought drier than normal conditions with hot summers and mild winters resulting in a two-year regional drought. Following El Niño, the La Niña climate pattern has brought damp winds and higher than normal rainfall from the northeast, southeast and southwest during the 1999-2000 summer, easing the effects of the drought. Typically, most farms and vineyards begin irrigating by late December. However, this year most did not start irrigating until the beginning of February, because of the unusual weather conditions that prevailed during the duration of this investigation. Climate data are presented in Appendix A.-1.

### *1.4.4.3 Vegetation*

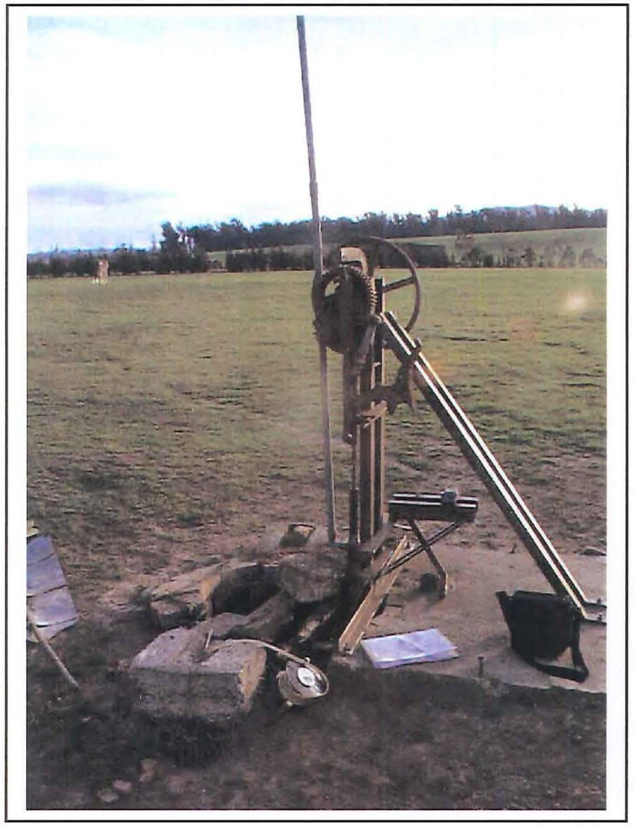
Ploughing, planting of exotic crops and grasses, fertilisation and grazing has significantly removed almost all of the native vegetation in the Waipara region. Exotic grasses, intermixed with clovers, gorse, broom and nasella tussock dominate the landscape in places where the land is not farmed (Department of Land and Survey, 1976; Rossiter, D., pers. comm., 1999). Nearly all of the land in the valley including the sloping hills and tilted terraces is used for pastoral and crop farming, horticulture and viticulture, with exotic forests predominating on steeper slopes and mountainous terrain.

## *1.5 Water-Use and Development*

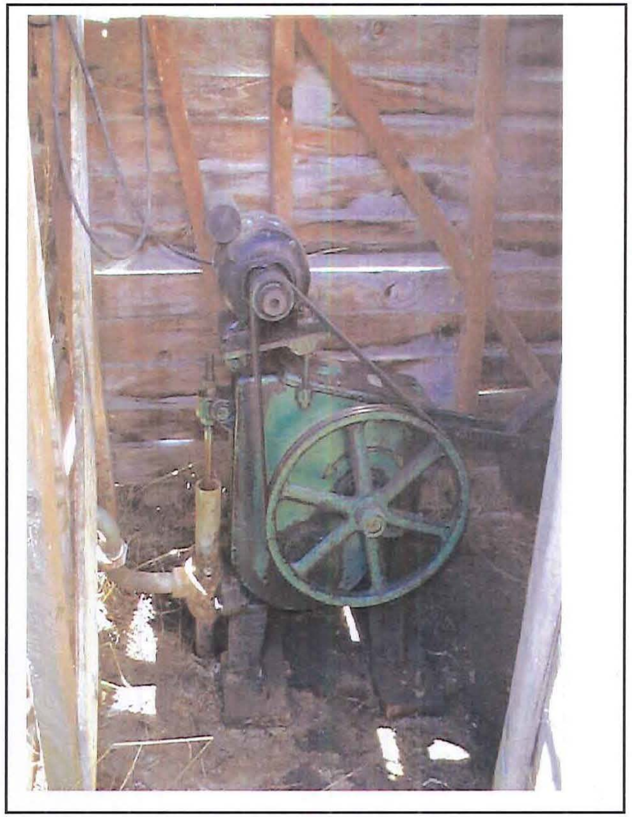
In the latter part of the last century, domestic and stock water supplies throughout the region was supplied by wells, infiltration and open galleries, in conjunction with surface storage facilities. The oldest wells in the region were most likely put down in the early 1900's, and were hand-dug, brick-lined wells, ranging from 2 – 12 metres deep, and 700 – 1200 mm in diameter (Figure 1.10a). These wells were used for domestic and stock supply and were capable of yielding a 'good' supply of water for these purposes (Upritchard, E., Croft, B., and Harris, B., pers.comm., 1999). However, many of the older shallow wells were proved to be unreliable as they would dry up during prolonged periods of drought, and in some cases every summer, with the decline in the water-table. The most reliable of the older wells are located adjacent to the Waipara River or local streams such as the Omihi Stream and Home Creek, suggesting that the water being extracted was derived from the nearby surface supply. Many of the existing shallow wells are contaminated with nitrates originating from the use of fertilisers and faecal coliforms, originating from intensive long-term pastoral farming and/or from septic tanks. Contamination may also have occurred as a result of surface runoff entering wells without protective covering and/or due to rain seepage into the ground, especially following the winters when the water-table is high and infiltration is most effective. The majority of the shallow wells that have proved to be reliable throughout the years are used primarily for stock and gardening because the degraded water quality.

As the demand for water increased in the 1940's – 1950's due to population growth, in Amberley and Waipara, and contamination of shallow aquifers occurred (Brown, L., pers.comm., 2000), many deeper, 75-100 mm diameter, steel wells were drilled. The wells were pipe-driven wells, ranging from 20 – 40 metres deep, not screened or slotted along the length of the aquifer. They were pumped with a reciprocating pump or

## *Figure 1.10 – Photographs of Disused Wells Installed in the 1940's and 1950's*



a) Brick-lined well



b) 100 mm well with reciprocating pump

c) Windmill-driven well

windmill (Figure 1.10b and Figure 1.10c), and were acceptable for domestic and stock supplies. However, many of these wells are disused, particularly those located in the townships, as they were not able to supply the increasing population demands. They were replaced by the County Water Scheme, which extracts water from the Ashley and Hurunui Rivers rather than the Waipara River, after several unsuccessful attempts were made to find an adequate supply near the Waipara River (J. Weeber 2000, pers.comm.). However, some of these older wells are still in use and according to their owners have consistently provided a reliable supply of water for stock and domestic use throughout the years (M.Casey, B. Harris, T. Whyte. 1999, pers.comm.).

In the early 1970's, drought and changing market economies put greater pressure on farmers in the Glenmark district to seek alternative sources of water, resulting in the engineering and construction of the Glenmark Irrigation Scheme (Wilson, 1983). The scheme dams water from the Weka Creek during high flows and pumps it to open storage facilities ranging in capacity from 90,000 to 220,000 m$^3$ (Figure 1.11). The scheme enables farmers to irrigate all-year round, significantly contributing to the development of the horticultural industry in the region.

***Figure 1.11 – Glenmark Irrigation Scheme Storage Facilities***

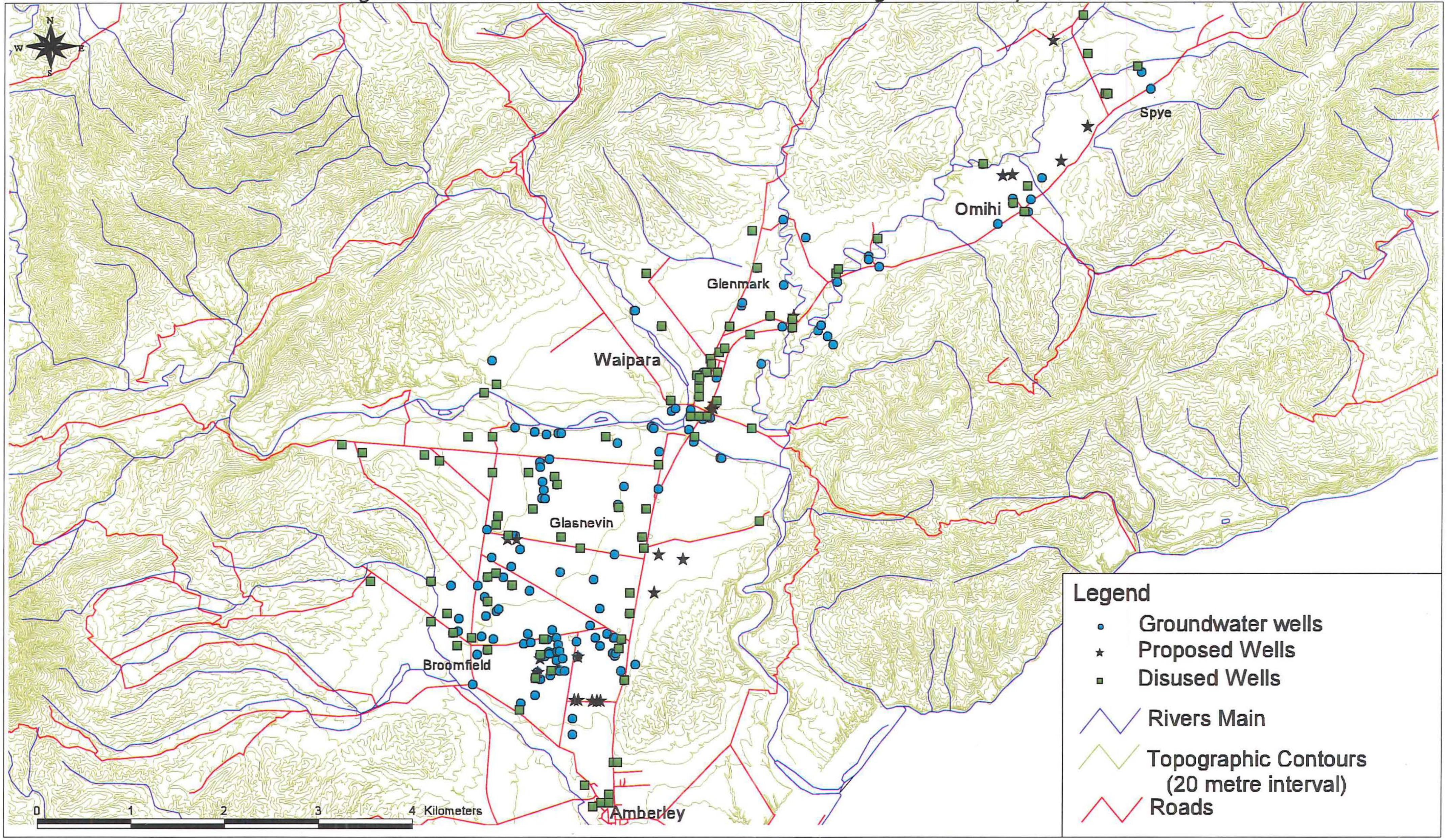
At present, the region is experiencing population growth and land development. Large farms are being subdivided into smaller lifestyle blocks, and landowners are drilling wells on each block in order to satisfy the Hurunui District Council development regulations, which requires developers to supply each subdivision with enough water for a domestic supply (i.e. 20 $m^3$/day). In the last two years, ECAN received 65 bore consent applications. In addition, there has been an increase in groundwater abstraction applications for domestic and irrigation purposes. This highlights the importance of groundwater in maintaining the area development, the rate at which the region is developing, and the way in which the groundwater resource is being utilised.

Approximately 280 wells were identified in the study area through the ECAN Wells Database (Figure 1.12). A letter of introduction with a brief questionnaire was sent to 140 residents to collect data about existing wells that were not previously in the ECAN database. A total of fifty new wells were identified, inspected and entered into the ECAN database. In addition, the residential responses were used to cross-reference the existing data. Field visits were made to all wells to maintain quality assurance. Shallow wells (2-20 metres deep) make up 46% of the total wells in the region, 42% are between 20 and 42 metres, and 12% are deeper than 42 metres. Of the 280 wells in the valley, 60% are in use. The remaining disused wells include foundation and investigation bores, several 75mm driven pipe wells, and old shallow wells, which were most likely hand-dug in the early part of the 20th century. Fifty percent of the wells presently in use were drilled in the last 10 years, and are primarily used for domestic, stock and irrigation supplies. A total of 53 new wells were drilled in the last two years, compared to a total of 10 in 1997-1998. Approximately, 30 wells are proposed to be drilled in the next 2 years.

## *1.6 Previous Work*

There have been several studies in the last 30 years that which have focused on both the geology and the hydrogeology of the region. The most comprehensive geological publication to date is Wilson's *Geology of the Waipara Subdivision* published by the New Zealand Geological Survey in 1963. Wilson's work provided a synthesis of the geology of the region by compiling all the relevant work completed from the late 19th century up until the early 1960's. The more significant studies include studies

*Figure 1.12 - Distribution of Groundwater Wells throughout the Waipara Basin*



completed by McKay (1887), Speight (1915), Thompson (1920), Jobberns (1937), Collins (1939), Mason (1941), Gregg (1950), and Wilson (1955). Recent detailed geological studies demonstrate how the regional tectonic environment has influenced the development of geomorphology, and have helped to provide some constraints on the timing of events by studying the stratigraphy (Harris, 1983), structural geology and geomorphology (Yousif, 1987; Nicol, 1991; Campbell and Nicol, 1992; Nicol et al., 1994). Figure 1.3a is a compilation of the most recent geologic mapping completed in the last 15 years, and was generated by the Natural Hazards Research Centre (NHRC) of the University of Canterbury. Figure 1.3b was produced from the 1963 NZGS 1:63,000 geological map of Hurunui District (sheet 18). Once the area north of Omihi is remapped, the data will be added to the NHRC database and North Canterbury map sheet.

Prior to 1972, no published hydrogeological studies existed. In 1972, a group of students from Lincoln University, under the supervision of Neil Borrie, conducted a small hydrogeological study of the Glenmark – Waipara area. The objective of the study was to assess the irrigation potential of the Waipara-Glenmark area based on data collected from existing wells. The study included a reconnaissance survey of local wells and a potentiometric survey to ascertain the groundwater flow direction. From this study it was concluded that the existing wells in the Waipara district wells could not provide a viable water resource for irrigation purposes.

A decade later, Brown and Weeber (1982) collected and compiled data from all known groundwater wells located between the Ashley and Waipara Rivers for a New Zealand Geological Survey (NZGS)/Department of Science and Industrial Research (DSIR) publication. Data collected included well location, depth, diameter, maximum and minimum water levels, well stratigraphic logs, well yields and chemical data when available. Compiled data was transferred to the ECAN Wells Database in 1990. In 1983, after the completion of only 10 of the proposed 28 water storage facilities built under the Glenmark Irrigation Scheme, Wilson briefly summarised the potential groundwater resources of Waipara-Glenmark region, and speculated as to whether they could support irrigation supplies. Wilson's unpublished report was the first hydrogeological assessment of the region, but focused only on the Waipara-Glenmark region.

Several published and unpublished reports have been produced in the last 10 years by ECAN. Graham Horrell in an unpublished report completed assessment of annual evaporation and precipitation distribution of the Waipara catchment in 1992. In 1993, ECAN published a resource management plan for the Waipara region (CRC Report 93/7). In 1996, Pattle Delamore assessed the potential affects of surface water abstractions on stream depletion for the Waipara River (CRC Report U96/53). This is the first comprehensive study of the hydrogeology of the Waipara Basin.

## 1.7 Research Methods

Prior to this study, the last well surveys of the Waipara Region were completed in 1982 (Brown and Weeber, 1982) and 1983 (Wilson, 1983). Therefore, field visits and quality assurance (QA) investigations were completed for a total of 264 wells identified through the ECAN database and by residential responses to written surveys. QA investigations were carried out in order to update the ECAN Wells Database, and to confirm that the pre-existing information in the database was correct. Approximately 40 wells were selected throughout the region for bi-monthly monitoring of water levels. Qualitative assessment of the regional groundwater resources was completed by analysis of data compiled in the ECAN Wells Database, interviews with residents, on-site geological logging and sampling during the drilling of wells, potentiometric surveys and bi-monthly monitoring of selected wells. Quantitative assessment of the aquifer parameters was completed by conducting constant discharge aquifer tests, as well as gathering data compiled by residents, drilling companies and private consultants. Chemical sampling of selected wells was completed in order to characterise the groundwater chemistry, to identify sources of groundwater recharge, and to help constrain the direction of groundwater flow by identifying common chemical signatures of aquifers. Isotopic sampling with Dr. Mike Stewart from the Institute of Geological and Nuclear Science (IGNS) was carried out for selected wells to characterise the age of the water at different depth aquifers and aid in the identification of recharge areas. A survey of springs was carried to aid in the assessment of groundwater-surface interaction, sources of recharge and discharge. Gauging of the Waipara River, and assessment of existing data supplied by the ECAN Surface Hydrology Environmental Monitoring Section were completed to identify losses and gains associated with interaction with the groundwater resources. Geophysical surveys using time-domain electromagnetic (TEM) and resistivity methods were employed in selected areas potentially to identify and map water-bearing units, and to identify different hydrogeological regimes based on their geophysical properties. Gravity surveys were completed to constrain depth to basement (i.e. Tertiary sequences) and identify any structural features that may affect groundwater flow.

## 1.8 Thesis Format

The thesis is presented in six chapters. Initial investigations revealed that two hydrogeological regimes could be distinguished within the Waipara Basin. The regimes can be distinguished based on geologic characteristics, geophysical properties, aquifer parameters, and chemical characteristics. Each chapter aims to highlight these differences. Chapter Two discusses the hydrogeological development of the Waipara Basin, and presents a conceptualised model of the hydrogeologic system. Chapter Three presents geophysical data. Chapter Four aims to identify and define the water resources of the Waipara Basin in terms physical and hydrologic properties. Chapter Five presents water chemistry and isotope data and analysis.
Chapter Six summarises data presented in Chapters two through Five, discusses resource management strategies for the Waipara Basin, and suggests future work.

# CHAPTER TWO
# GEOLOGY AND GEOMORPHOLOGY

## 2.1 Introduction

This chapter describes the geology and geomorphology of the Waipara Valley. The first section of the chapter discusses the structural development of the valley in relation to the regional tectonic environment. A summary of the local stratigraphy is presented with an emphasis on the alluvial deposits, which form the principal water-bearing formations. Geomorphic surfaces are discussed in relation to aggradation and degradational events. A discussion of these events aims to demonstrate the complex nature of the depositional history that contributed to the development of the Waipara Basin hydrogeologic regime (s). A conceptual model of the hydrogeology is presented.

## 2.2 Structural Development of the Waipara Basin

Early Cretaceous folding and uplift during the Rangitata Orogeny resulted in the formation of a northwest striking and plunging syncline cutting across the Doctor's range (Wilson, 1963, 1983), (Figure 1.3a). Prior to the Cenozoic, regional folding accommodated much of the deformation in response to faulting of the rigid basement (Bradshaw, 1975; Campbell and Nicol, 1992). In the Cenozoic, the development of the convergent plate boundary marked the beginning of the Kaikoura Orogeny, and reverse/thrust faults and fault-propagated folds formed narrow basins between large asymmetrical anticlinal folds to accommodate differential uplift. The structural geometry changes across the region. The western margin of the basin is bounded by the eastward verging Mt Grey and Karetu thrusts, whereas in the east, it is dominated by the westward verging Omihi and Hamilton Faults, and southeast propagating folds, such as the Cass (Kate and Black) Anticline, (Figure 1.3a, back pocket). Accelerated erosion of topographic highs due to increased tectonic activity and climatic fluctuations in the Quaternary resulted in infilling of the Waipara Basin with a massive quantity of gravels. Late Pleistocene and Holocene deformation is evident in a variety of structures and geomorphic features (Yousif, 1987; Nicol, 1991; Campbell and Nicol, 1991; Nicol et al., 1994; Pettinga and Armstrong, 1998). A variety of interference structures have developed from the reactivation of older extensional structures formed in the

Cretaceous, and the development of younger structures associated with the Cenozoic convergent plate boundary (Pettinga and Armstrong, 1998).

## 2.3 Stratigraphy

Geologic maps are presented in Figures 1.3a and 1.3b (back pocket). A stratigraphic section is presented in Figure 2.1 as described by Browne and Field (1985) and Nicol (1991).

### 2.3.1 Triassic to Late-Cretaceous Rocks

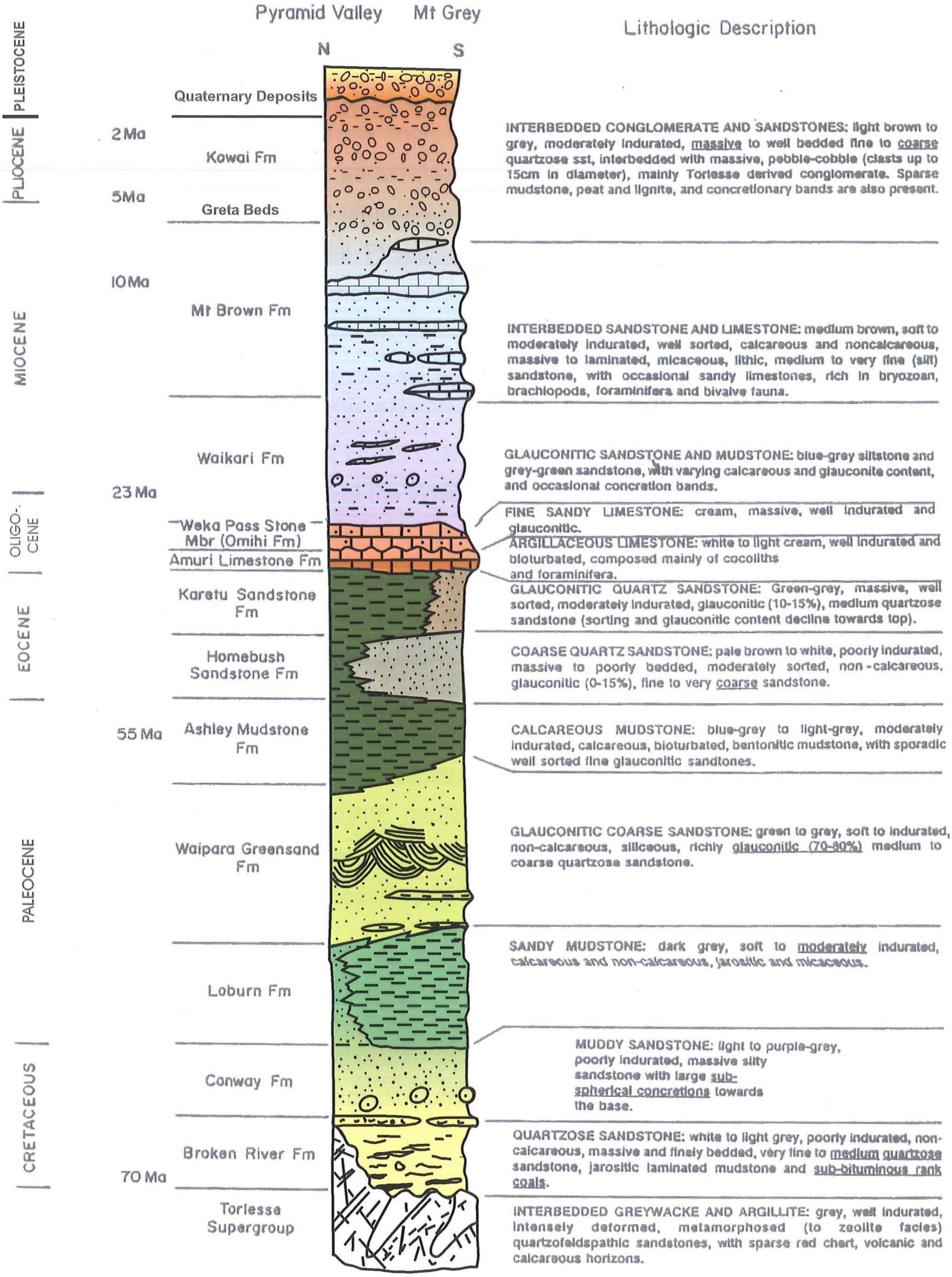
Basement consists of a suite of Mesozoic quartzo-feldspathic greywacke and argillite of the Torlesse Supergroup (Bradshaw, 1972). Torlesse lithologies are dominated by massive sandstones, interbedded fine sandstones and mudstones, with sparse volcanics, red cherts, and slightly calcareous horizons. Torlesse rocks are exposed in the cores of the Black and Cass Anticlines along the eastern margin of the basin; in the Onepunga and Doctors anticlines to the west, and on the upthrown side of the Grey Fault along the southwest margin of the valley as shown in Figure 1.3a (back pocket). Cretaceous deposits consist of basal coal seams overlain by fine-grained sandstones and mudstones (Broken River and Conway Formations). Shell beds and fossiliferous concretions are common and mark a marine transgression in the late Cretaceous (Browne and Field, 1985). The best exposures are found west of the valley on the up thrown side of the Boby's Creek Fault.

### 2.3.2 Tertiary Sedimentary Deposits

Tertiary deposits form the topographic highs along the margins of the basin, flanking the limbs of the anticlines and synclines (frontispiece). Tertiary deposits rest unconformably on the Cretaceous rocks. Early-Tertiary sequences included sandy micaceous mudstones (Loburn Formation) and glauconitic sandstones and mudstones (Waipara Greensand, Ashley, Homebush, and Karetu Formations). The Ashley Mudstone rests unconformably on the underlying Waipara Greensand (Thompson, 1920; Wilson, 1963; Browne and Field, 1985; Nicol, 1991).

The Oligocene marks a change in depositional environment to deeper water with the

***Figure 2.1 - Local Stratigraphic Column for the Waipara Valley***
(Modified from Nicol, 1991)



deposition of the Amuri and Weka Pass limestone Formations (Andrews,1963; Browne and Field, 1985). Much of the Amuri Limestone appears to have been exposed to erosion during the Oligocene following post-depositional uplift and faulting (Browne and Field, 1985). The Weka Pass Formation rests unconformably on the Amuri Limestone. The limestones are potential aquifers and/or a source of recharge to the basin. The end of the Tertiary is marked by a gradual lowering of sea level as the climate became colder, and is reflected in the stratigraphy by a gradual coarsening of sediments in the Waikari, Mt. Brown and the Late Pliocene Greta Beds (Speight, 1919). The Late Pliocene Greta Beds grade into the early Pleistocene Kowai Gravels (Thompson, 1920; Gregg, 1959).

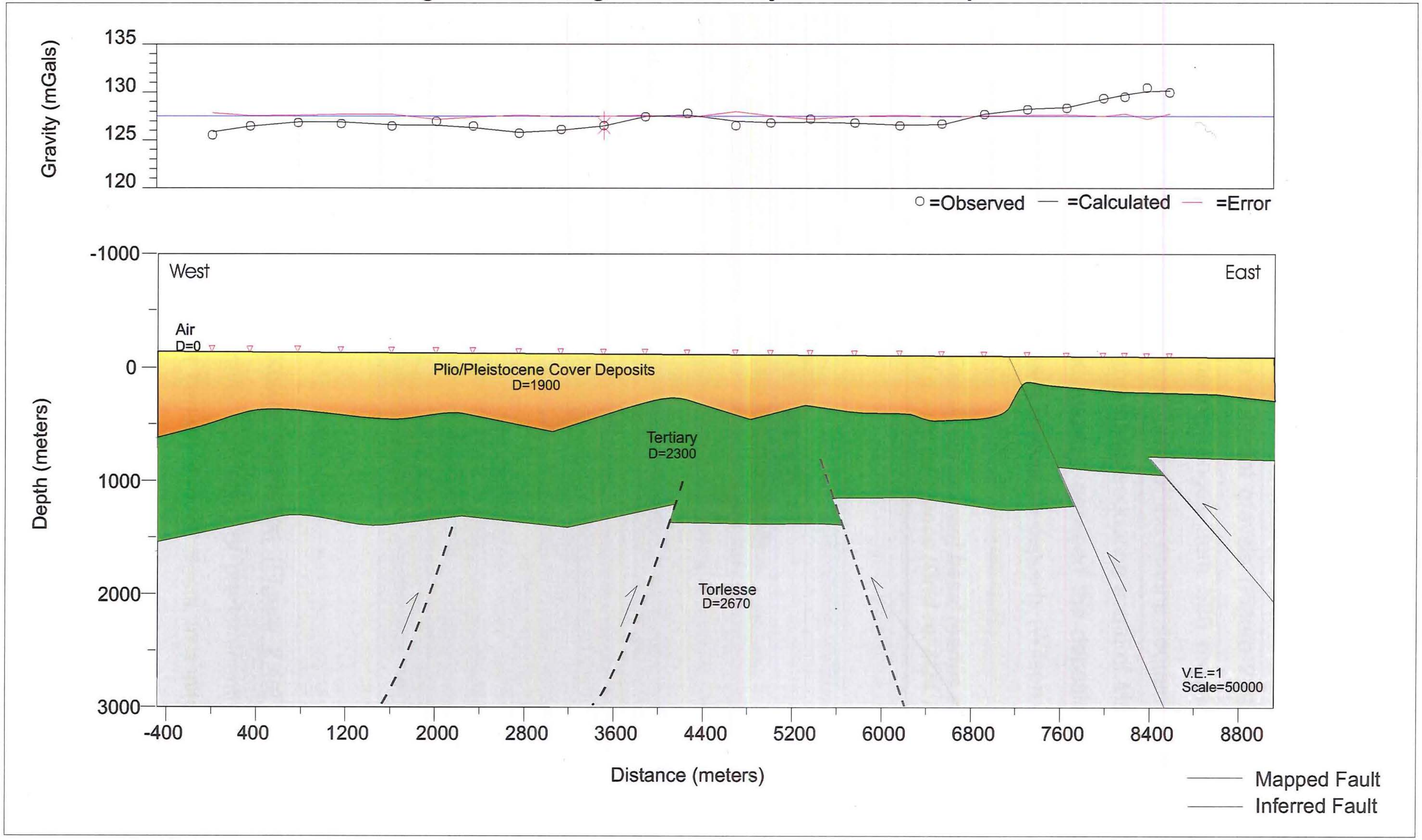
### 2.3.3 Depth to Basement

Depth to basement is not well constrained and varies throughout the basin. The basement depth is greatest east of the Waipara township. Basement depth decreases in the north and increases in the southern part of the basin (Wilson, 1963, 1983). Previous studies suggest depth to basement in the central part of the basin to be approximately 1000 – 2000 metres (Wilson, 1963). Gravity surveys completed as part of this study estimate the basement depth to be between 800 - 1000 metres in the northern part of the basin (Spye), and between 1000 –1500 metres in the vicinity of Georges Road, Waipara area. Depth to basement in the southern part of the basin (Broomfield-Amberley) is poorly constrained. Wilson's model suggests the depth to be greater than 1000 metres. Best-fit models for the gravity data suggest that the basement topography is undulating, and interrupted by mesoscale faulting at depth (Figure 2.2). Processing and modelling of the gravity data are presented in Chapter Three.

### 2.3.4 Quaternary Deposits

Wilson (1983) identified four types of alluvium formed during the Quaternary: post-glacial alluvium (recent), periglacial alluvium (Canterbury Gravels), interglacial alluvium (Teviotdale Gravels) and pre-glacial alluvium (Kowai Gravels) derived from the erosion of newly exposed formations associated with the Kaikoura Orogeny (Wilson, 1983).

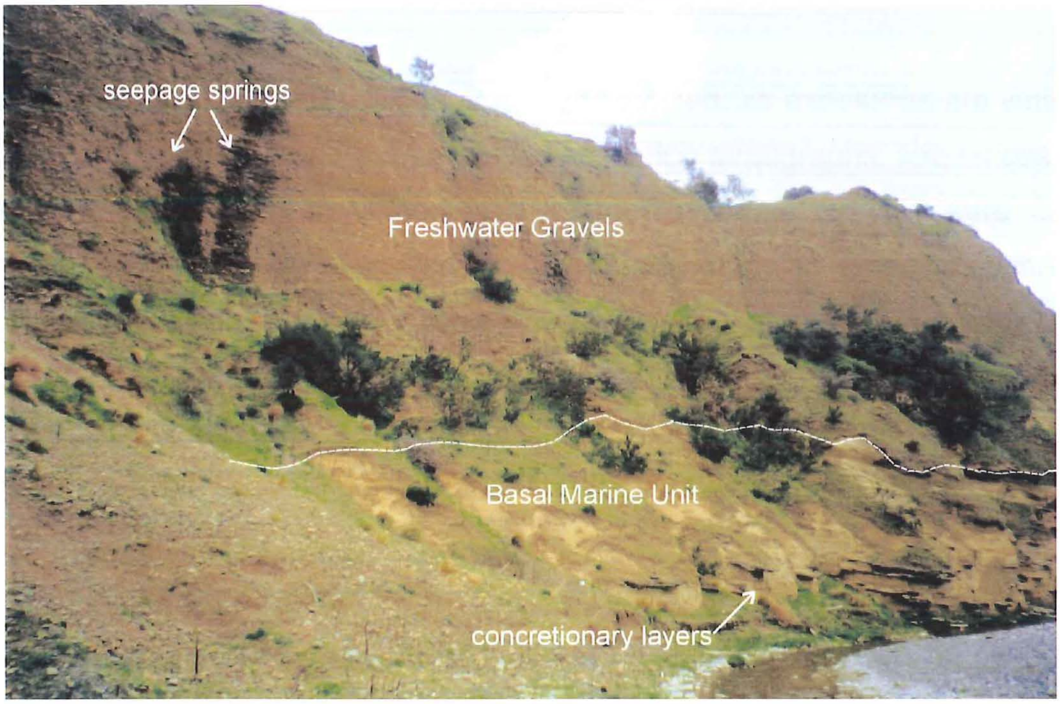
## *Figure 2.2 - Georges road Gravity Model and Interpreation*



#### 2.3.4.1 Kowai Formation

The early Pleistocene deposits of the Kowai Formation consist of moderately indurated fine sandstone and blue siltstone with intermittent layers and lenses of rounded pebbles, overlain by a thick sequence of fluvial gravels (Figure 2.3). The estimated thickness of the original Kowai Formation ranges from 580 metres to 650 metres (Browne and Field, 1985). However, exposures of the marine sequence range from 30 to 150 metres, whereas exposures of the fluvial sequence south of Mt. Grey reach 250 metres (Wilson, 1963). A long period elapsed between the deposition of the Kowai Gravels and the younger Late Quaternary Teviotdale deposits (Wilson, 1963).

***Figure 2.3 – Contact between Lower Kowai (Waitotaran) basal marine sequence and the Upper Kowai (Nukumaruan) fluvial gravel sequence (Grid ref M34:79605-93850)***




##### 2.3.4.1.1 Kowai Gravels

The Kowai Gravel member of the Kowai Formation (Figure 2.4a) is composed of weathered, limonite stained fluvial gravel consisting of predominantly greywacke and argillite gravels, and to a lesser extent Tertiary derived clasts, in a silty clay matrix. The gravel is poorly sorted, and rounded to subangular. The matrix is composed of fine sand, silt and clay in varying proportions. Deposition of the Kowai Gravels occurred following the recession of the sea as a result of uplift associated with the Kaikoura

Orogeny and/or the beginning of Late Pliocene glacial-interglacial climate changes approximately 2 Ma (Wilson, 1955; Wilson, 1963; Wilson, 1983;).

#### *2.3.4.2 Teviotdale Gravels*

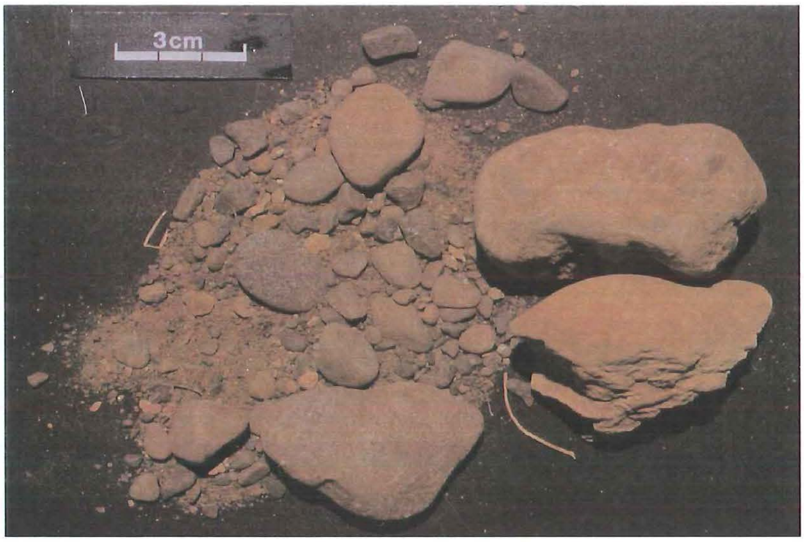
The Teviotdale Gravels lie unconformably on the older sequences. Like the Kowai Formation, the Teviotdale Gravels are composed predominantly of greywacke and argillite clasts with a smaller percentage of Tertiary-derived clasts (Figure 2.4b). The gravels exhibit a creamy brown leached colour with yellow-brown fine sand and silty matrix (Wilson, 1963). The maximum thickness of the gravels is likely to be 100 metres (Wilson, 1963). Everywhere throughout the valley, the exposures of the Teviotdale gravels are tilted and indicating that deformation occurred concurrently with deposition or soon after (Campbell and Yousif, 1987; Nicol et al., 1994).

The time and duration of deposition is not well defined, as exposures are limited within the basin, and materials and markers used for dating stratigraphic sequences have not been found. According to Wilson (1963), the Teviotdale Gravels were most likely deposited during a period of low sea level that accompanied an early advance of the Otiran glaciation (Wilson, 1955; Wilson, 1963;). However, recent work completed by Phil Tonkin of Lincoln University suggests that the Teviotdale may represent remnants of several basin cut and fill cycles with significant time intervals in between that may have take place over the last 100,000 to 200,000+(?) years (P. Tonkin, pers.comm., 2000).

#### *2.3.4.3 Canterbury Gravels*

The Canterbury Gravels are the youngest of the gravel sequences (excluding the deposits on the modern day floodplains). They are deposited unconformably on the Teviotdale Gravels (Figure 2.4c). They are largely composed of greywacke gravels with a smaller percentage of silt and clay matrix than the Teviotdale Gravels (Wilson, 1963). The Canterbury Gravels are predominantly clast supported compared to the Teviotdale Gravels, which exhibit a higher proportion of matrix (Wilson, 1963). The thickness varies throughout the region and range from 2 metres to 30 metres (Wilson, 1963). The Canterbury Gravels are found throughout the basin on the broad aggradation surface between the present day stream courses. The Canterbury Gravels are believed to have

**Figure 2.4 – Photographs of the Kowai, Teviotdale and Canterbury Gravels**




a) Kowai Gravels, Waipara (Grid ref. M34: 79605-93850).

b) Teviotdale Gravels, The Mound (Grid ref. M34: 87799-93050)

c) Canterbury Gravels, The Mound (Grid ref. M34: 87799 –93050).

been deposited during the last advance of the Otiran glaciation, which ended approximately 10,000 – 14,000 yrs ago (Harris, 1982; Campbell and Yousif, 1987).

Aggradation of the mid-to-late Pleistocene gravels in the central part of the basin, dammed the Omihi Valley (northern region of the basin) resulting in the formation of local base level control (J.Campbell and P.Tonkin, pers.comm., 2000). Recent pedological studies carried out by Phil Tonkin of Lincoln University, and examination of stratigraphic logs and drill cuttings collected during this study suggest that the source and depositional environment responsible for depositing the alluvium in northern part of the basin is different than that of the south. Deposits in the northern region seem to represent a variety of facies with high proportion of Tertiary derived clasts. Harris (1983) inferred that the Canterbury Gravels in the Waipara-Omihi area were deposited by a slow meandering river system based in the facies. The deposits south of the Waipara township are dominated by greywacke and argillite clasts, with fewer sedimentary facies, and it is suspected that they were deposited by a braided river system deriving alluvium from the Waipara catchment. Based on these findings, it is proposed that the Canterbury Gravel deposits of the northern region and southern region of the basin be recognised as two separate, time-equivalent units derived from separate sources. It is suggested that the northern deposits be referred to as the Omihi Gravels, and Waipara Gravels for the southern deposits.

Recent deposits are located on the present day flood plains, and form thin veneers on degradation terraces adjacent to the rivers and streams.

### 2.3.5 Correlation with Canterbury Gravel Formations

Table 2.1 summarises the time-stratigraphic relationship and the inferred depositional environment associated with regional events for the Kowai Formation, Teviotdale and Canterbury Gravels. Tentative correlations of Waipara Basin deposits with central Canterbury stratigraphic units are listed. Data presented in the Table 2.1 are compiled from a variety of literary sources, as well as discussions with persons who have recently completed work within the study area. Time-scale and regional events are presented as

***Table 2.1 – Stratigraphic Relationship between Waipara Pliocene and Quaternary Deposits, Regional Events and Correlation with Canterbury Plain Formations.***

| International Divisions | | | New Zealand Subdivisions | | | Began Years Ago | Geological Unit* | Geological Unit (Wilson, 1963) | Correlation Canterbury Plains | Regional Events | Facies |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Period | Epoch | | Epoch | | Climate (Suggate, 1985) | | | | | | |
| Quaternary | Pleistocene | Holocene | Hawera | Recent | Aranuian | 10,000 | Recent Deposits | Recent Deposits | Recent Deposits | Glacial Retreat Tectonically Inactive? | Braided Alluvium |
| Quaternary | Pleistocene | Late Pleistocene<br>Mid- Pleistocene | Hawera | Hawera | Otiran | 70,0000 | Canterbury Gravels[1]<br>waipara gravels<br>omihi gravels | Canterbury Gravels<br>Teviotdale Gravels | Burnham[4]<br>Windwhistle[5] | At least 2 stages of advance separated by interglacial periods; minimal tectonism | Periglacial Outwash<br>Braided River<br>Meandering Plain |
| | | | | | Kaihinuan | 120,000 | Teviotdale Gravels[2] | | Woodlands[5] | Glacial Retreat | Periglacial and interglacial fluvial deposits representing several cut and fill cycles |
| | | | | | Waimean | 200,000 | | | | | |
| | | | | | Karoroan | 250,000 | ? | | | | |
| | | | | | Waimaungan | 310,000 | | | | Glacial Advance | |
| | | | | | Scandinavian | 350,000 | | | | | |
| | | | | | Nemonan | 380,000 | | | | | |
| Quaternary | Pleistocene | Early Pleistocene | Wanganui | Nukumaruan - Castlecliffian | | 1,800,000 | Kowai Formation<br>Kowai Gravels | Kowai Formation<br>Kowai Gravels | Kowai Formation[6] | Uplift, folding and faulting, followed by erosion, forming present landscape of the Southern Alps Kaikoura Orogeny | Fluvial |
| Tertiary | Pliocene | | Wanganui | Opoitian – Waitotaran | | 7,000,000 | Greta Beds[3] | Greta Beds[3] | | | Marine – estuarine (near-shore, shore line, low tide level |

* Proposed time-stratigraphic relationship for Waipara Basin Quaternary deposits; suggested scheme is based on recent published and unpublished work by J.K. Campbell (University of Canterbury), P. Tonkin (Lincoln University), and information gathered during this study.
[1] Suggested names for proposed unit subdivision of time-equivalent Waipara Basin Canterbury Gravels
[2] Jobberns (1937a), Campbell and Yousif (1989) and Tonkin (pers.comm., 2000) included the Teviotdale in the Waimean stage
[3] Nomenclature as stated by Speight (1919), after Browne and Field (1985); Synonymous with the Greenwood Formation of Gregg (1959).
[4] Correlated by Gregg (1964)
[5] Suggate (1965)
[6] Inferred correlation

outlined by Brown and Wilson (1988); Campbell and Yousif, (1987)and Brown (1998).

Gregg (1964) correlated the Late Quaternary Canterbury Gravels with the Burhnam and Windwhistle Formations of the Canterbury Plains, and the Teviotdale Gravels with the Woodlands. This reinforced the suggestion of others that the Waipara Basin represents the northern continuation of the Canterbury Plains (Wilson, 1955). However, examination of lithological logs from groundwater wells extending from Waipara Valley southwards does not support this. The lithologies of strata penetrated by the wells south of Leithfield change from strata dominated by yellow claybound brown gravels to that of alternating fluvial gravels and grey-blue marine sand and silt, typical of the Late Quaternary deposits of the coastal North Canterbury Plains. It is suggested that local folding and faulting, perhaps associated with the Springbank Fault, resulted in the isolation of the Waipara Basin from the Canterbury Plains. This is reflected in the absence of marine depositional environments of the interglacial periods in the Canterbury Plains (Fields, G., 1999; Campbell et al., 2000; L. Brown, pers.comm.,2000). Other correlations listed in Table 2.1 are inferred based on the estimated time and duration of deposition.

## *2.4 Geomorphology*

### 2.4.1 Geomorphic Surfaces

There are five recognised geomorphic surfaces in the Waipara valley (Figure 2.5), (Wilson, 1963; Nicol et al., 1994). From oldest to youngest they are: the Teviotdale Surface, the Canterbury and Omihi Surfaces, the Weka Fan Surface and the modern degradation surface (Wilson, 1963; Wilson, 1983; Nicol et al., 1994).

The Teviotdale Surface is the oldest surface and is preserved as isolated loess-mantled remnants (Wilson, 1963), and is interpreted to be an aggradation surface, interrupted by several cycles of aggradation-degradation events (Campbell and Yousif, 1987). The Teviotdale surface sits approximately 15 metres higher than the Canterbury and Omihi Surfaces. The original Teviotdale surface is preserved at four localities (Figure 1.3a).

## Figure 2.5 - Geomorphic Surfaces of the Waipara Alluvial Basin

### Legend

**Topography**

20 Meter Elevation Contours

**Geomorphic Surface Succesion**

Modern Surfaces - degradational flood plain

Weka Fans (w)

Omihi Surface (o)

Canterbury Surface (c)

Teviotdale Surface

Unidentified Surfaces (?)

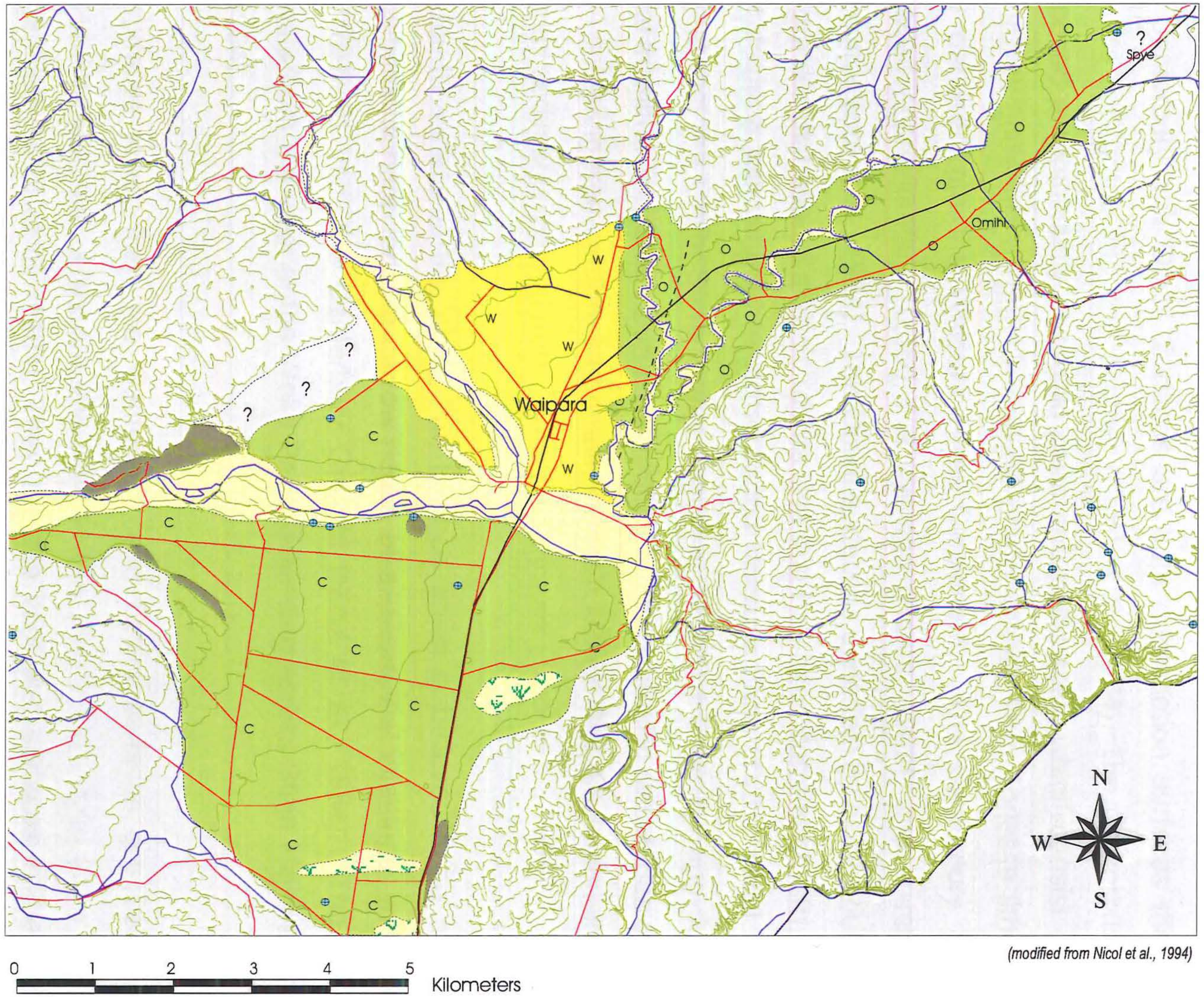
**Modern Geomorphic Features**

Rivers

Springs

Swamp

**Cultural Features**




*(modified from Nicol et al., 1994)*

The Canterbury and Omihi Surfaces are both aggradation surfaces that appear to coalesce and grade into one another (Nicol et al., 1994). The Canterbury Surface is composed predominantly of argillic pallic and pallic soils, which consist of sand, and clay loams underlain by gravels derived predominantly from Torlesse lithologies most likely derived from the Waipara River Catchment. The Canterbury Surface was aggraded approximately 10,550 ± 2 kyr ago (Harris, 1982), and is regarded as a minimum (Nicol et al., 1994). The Omihi surface is underlain by calcareous silts, sands and gravels that overlie a silicic tephra unit that has been correlated with the 22.6-kyr-old Aokautere Ash erupted from the Taupo Volcanic Zone (TVZ). Nicol et al., (1994) suggest that the Omihi Surface was aggraded 12,000 ± 2 kyr kyr ago during the last glacial maxima. The Omihi Surface is characterised by argillic calcareous orthic melanic soils containing free calcium carbonate, veriform fabrics that are underlain by pebbles, and clay sediments derived from Tertiary sequences (Nicol et al., 1994).

The fourth surface is the Weka Fan Surface which is believed to be a post glacial depositional surface forming narrow ridges of alluvium that interfinger with loess most likely derived from the Canterbury Gravels (Nicol et al., 1994). The Weka Fans originate from the west at the Weka Pass, extending across State Highway 1 (Nicol et al., 1994).

All surfaces lower than the Canterbury and Omihi surfaces are believed to be degradation surfaces. They are characterised by poorly developed stony orthic brown soil profiles (Nicol et al., 1994). They are the youngest surfaces in the region, and include both the degradation terraces and active floodplains of the Waipara River, Omihi Stream, Weka and Home Creeks as shown in Figure 2.5 (Nicol at al., 1994).

## *2.5 Influences on the Development of the Hydrogeologic System*

The aquifers investigated and assessed in this hydrogeologic study are found in the Kowai, Teviotdale and Canterbury Gravels. Assessment of the depositional, structural and geomorphological history of the Waipara Basin is vital to understanding the development of the hydrogeology, and spatial distribution of the aquifers.

### 2.5.1 Structural Influences on the Hydrogeology

Uplift and faulting associated with the Kaikoura Orogeny forced rivers and streams to adjust their bedloads, courses and channel morphology in order to maintain equilibrium (Ouchi, 1985; Campbell and Yousif, 1987; Campbell and Nicol, 1992). Tectonic activity resulted in the restriction of channels producing cut-off meanders and channel abandonment, resulting in a change in sedimentation. In addition, post-depositional uplift and faulting influenced the development of the hydrogeology by creating and destroying preferred paths of groundwater flow, thereby controlling the spatial distribution of aquifers. The spatial distribution of alluvial aquifers can be affected by faulting and surficial warping associated with fault-propagated folds. There are three identifiable structures that may have influenced the development of the hydrogeologic system: the Omihi Fault, the Mound Fault and the Amberley Structure (Figure 1.3a).

#### *2.5.1.1 Omihi Fault*

The Omihi fault is a SE striking segmented thrust fault, with limited surface expression, bounded at the base of the Black Anticline and possibly extending southwards towards the Amberley township (J.K. Campbell, pers.comm., 1999). Surface ruptures of the fault can be observed at two known localities in the region (Figure 1.3a). The first locality was described by Harris (1982) and is located along the bank of the Omihi Stream north of Mt. Cass Road in Waipara, and the second locality is in gully at the base of the Black anticline, NE of Baxter's Road in Omihi (Grid ref. N34: 94560-97017). The former locality exhibits movement and offset on gravel sequences (Harris, 1982; Nicol et al., 1994). The latter locality has a contact between disturbed gravels and limestone (Figure 2.6). However, it is questionable as to whether this represents a true faulted contact, a stratigraphic contact resulting from the deposition of gravels after the uplift and folding of the Black Anticline, or a landslip. Groundwater chemical data (Chapter Five) provide evidence that the Omihi Fault does affect the groundwater system, specifically by enabling recharge from the limestone to the adjacent gravels through fractures and possibly karstic features. Although, the Waipara Valley is not known for its karstic topography, sinkholes are a common feature on the limestone ridges to the east of the valley, and may be an important source of recharge (Figure 2.7a and 2.7b).

***Figure 2.6 – Possible Fault Contact Between Limestone and Gravels (Grid ref. N34:94711-9659).***

(Photo: B. Young)

***Figure 2.7 – Photograph Showing the Sinkholes that have developed on Black Anticline north of Reeces Road, Omihi (Grid ref. N34: 99850-97560).***


*a) sinkholes formed on ridge north of Reeces Road, Omihi*

*b) close-up of one of the many sinkholes present on the Black Anticline*

#### 2.5.1.2 The Mound Fault

The Mound (Figure 2.8) is a thrust fold asymmetric anticline composed of remnants of the older aggradational Teviotdale Gravels, rising 25 metres above the younger surface aggradational surface composed of Canterbury Gravels (Wilson 1963; Campbell and Nicol, 1992; Nicol et al., 1994). The Mound owes its existence to presence of an eastward dipping thrust fault concealed at depth (Figure 2.9). The gravels exposed in terrace scarp outcrop immediately below the Mound display increasing deformation with age. The overlying Canterbury Gravels, although gently tilted, do not show evidence of deformation. The only evidence that the Mound Fault has influenced the hydrogeology is the existence of a perennial spring that flows at the base of the terrace scarp, just east of the highly deformed gravels.

***Figure 2.8 – Looking Northeast to the Mound from Georges Road.***

#### 2.5.1.3 The Amberley Rise

Geomorphic mapping of springs and seepage areas lead to the identification of an east-west trending 1-2 metres rise in the land surface just north of the Stanton Rd - Watties Road intersection (Figure 2.10). The structure is located approximately 3 km north of Amberley downgradient of a swamp/wetlands. The structure extends approximately 2-3

***Figure 2.9 – Geologic cross-section showing the subsurface structure of the Mound as interpreted by Nicol and others (1994).***

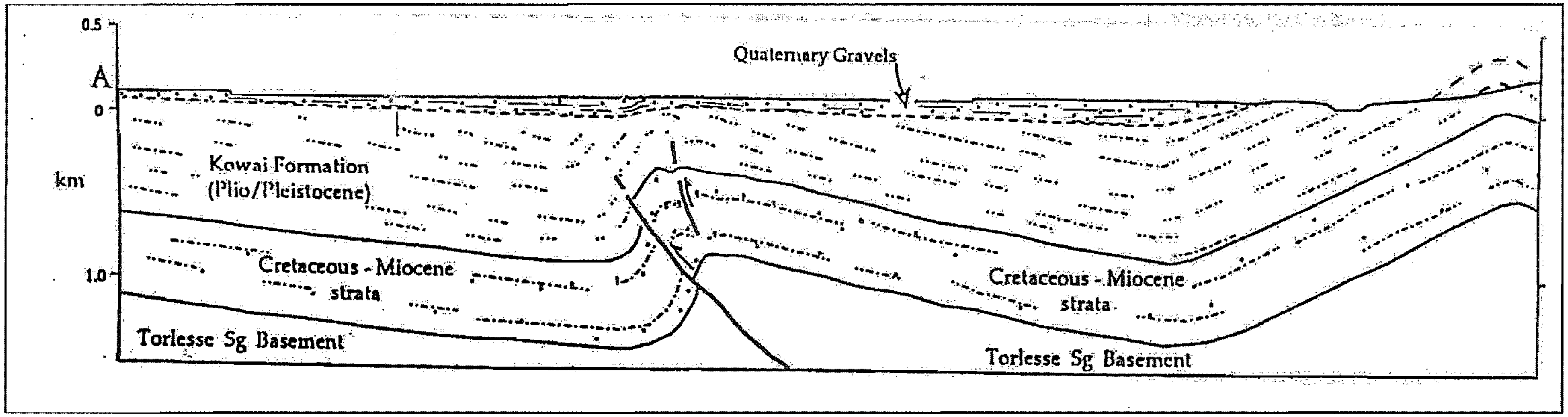


***Figure 2.10 – Photograph Showing the 1-2 metre ENE Rise Associated with the Amberley Structure (Grid ref. M34:86849-86380).***

*a) looking southwards along Stanton Road towards Amberley*

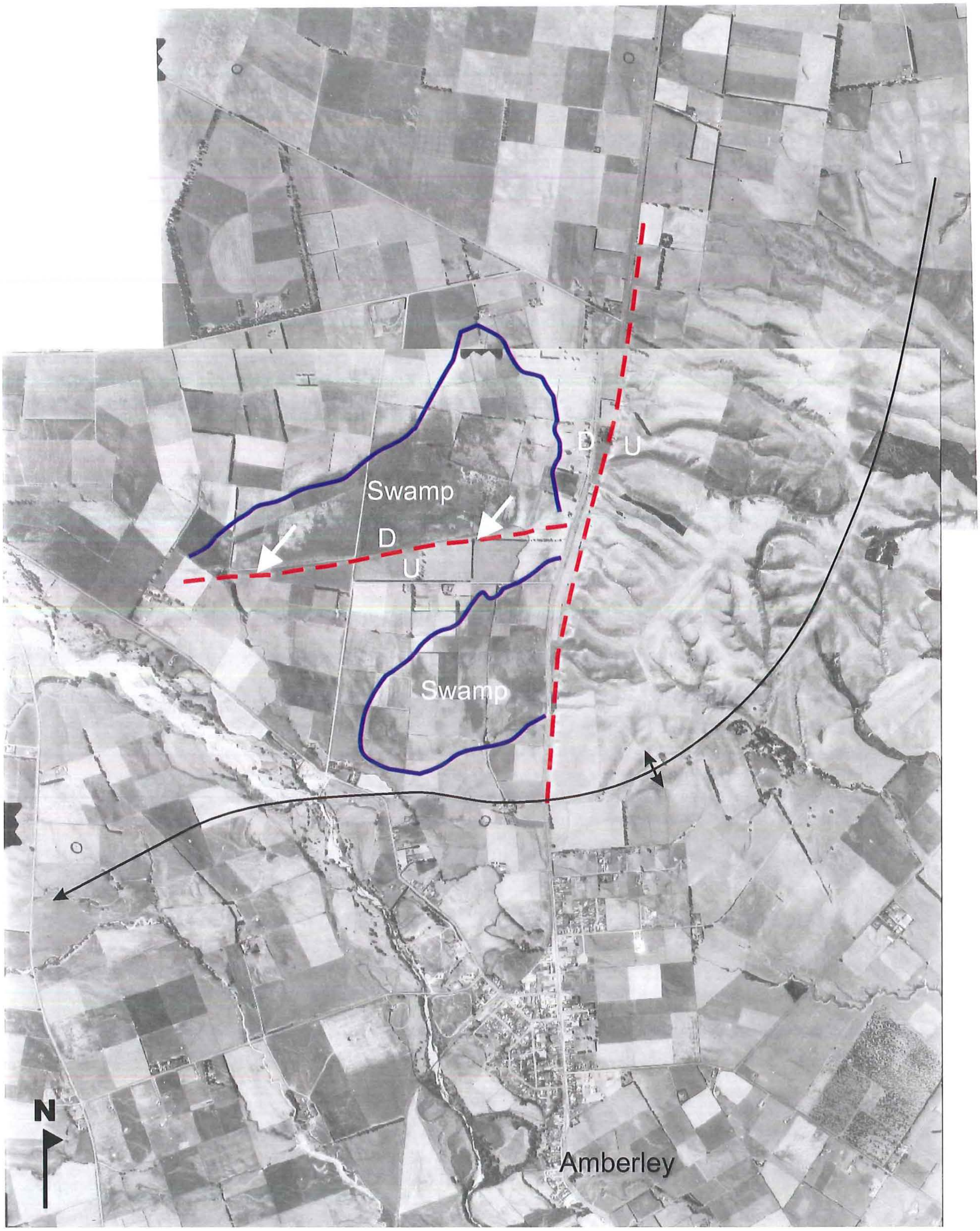
*b) looking northwards along Stanton Road towards Waipara* kilometres from just west of State Highway 1 to Douglas Road. Surficial warping diminishes towards Douglas Road. Both the swamp and the Amberley structure can be identified in an aerial photograph (Figure 2.11). A 1960's British Petroleum (BP) oil exploration seismic line conducted along Douglas Rd identified a fold in the underlying strata with the fold axis located approximately at the Douglas Road-Stanton Road intersection (R. Jongens, pers.comm., 2000). It is not known how the two structures are related. It is suspected that the Amberley Rise is responsible for the development of the northern swamp, and that the development of the Cass Anticline is responsible for the development of the southern swamp. Examination of Figure 1.7 – Soil Map of the Study Area shows a change in soil cover at this locality, which trends along the downthrown side of the structure (Chapter 1). Potentiometric surface contours for the area (Figure 2.12) suggest a convergence of groundwater flow towards the Amberley Rise, however, at present there is no evidence that the structures affect the flow of the groundwater at depth.

### 2.5.2 Depositional and Geomorphic Influences

The Kowai Gravels formed as alluvial outwash floodplains and fans during the rapid erosion of structural highs that followed the early Pleistocene cataclysmic movements of the Kaikoura Orogeny. The Kowai Gravels are largely concealed beneath the Waipara Basin in a structural trough (Wilson, 1963). Aquifers contained within the Kowai are suspected to be laterally continuous and uniform. However, because of the rapid rate at which erosion was occurring during the Early Pleistocene, the aquifers are expected to exhibit a wide range of sediment sizes and sorting.

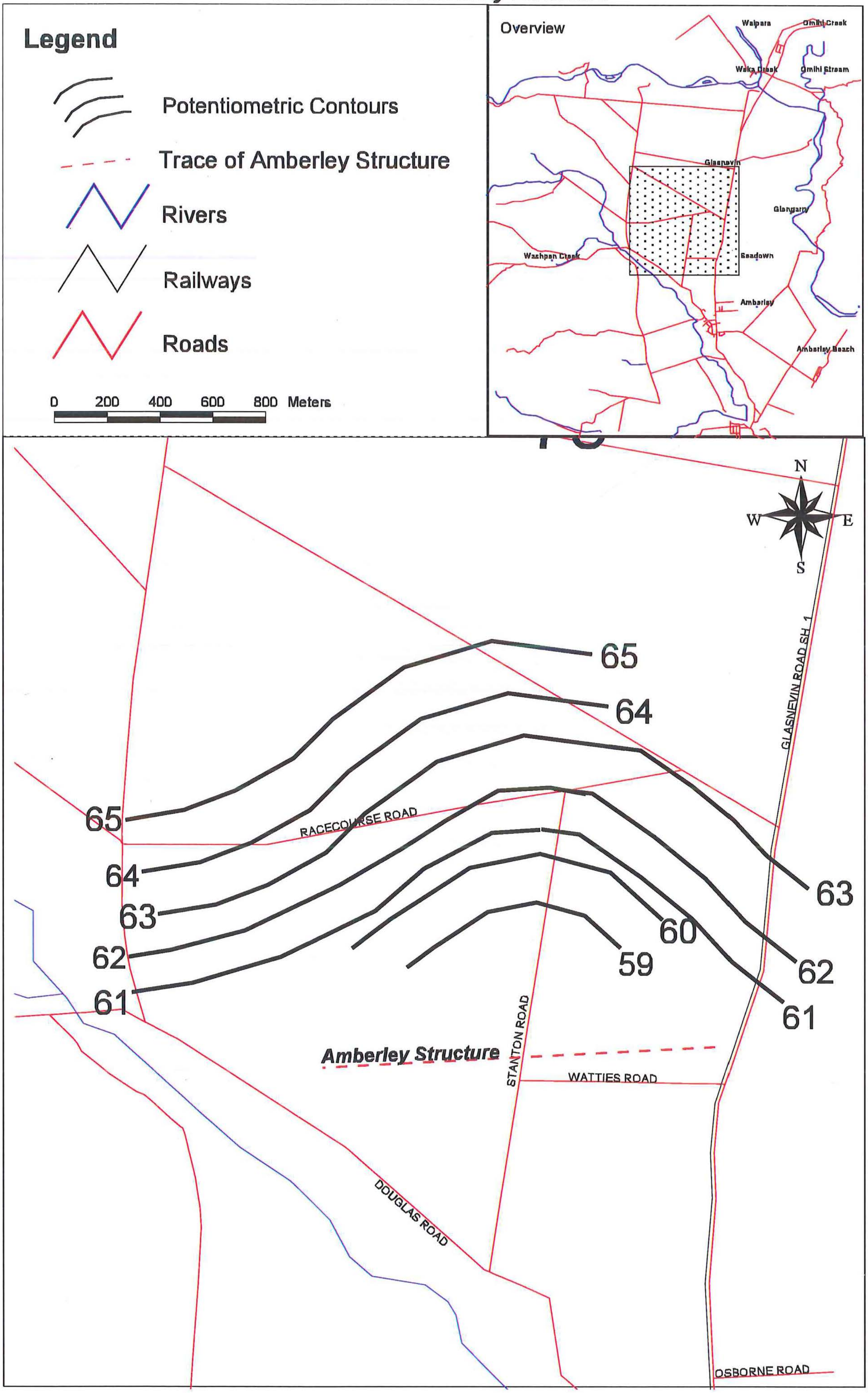
Mid-to-Late Quaternary deposition was largely controlled by climatic changes associated with glaciation, as rivers and tributaries reworked older deposits and downcut into the older aggradational surface during glacial periods. The broad Canterbury and Omihi aggradation surfaces were formed by coalescing fans being built up by the ancestral rivers of the Kowai and Waipara Rivers, the Omihi Stream, Weka Creek, and Home Creek, and possibly other paleo-rivers and tributaries that have persevered through time. In addition, channel morphology and the rate of incision into the underlying surface were influenced by local tectonic activity. Channel morphology

***Figure 2.11 - Aerial Photograph showing the Amberley Structure.***




White Arrows are pointing to the ENE trending structure. Directly north of the structure a swamp (outlined in blue) has developed. A swamp area has also formed to the south of the Amberley Structure, and is located adjacent to the axial trace of the Cass Anticline. The N-S trending red line to the east of the structure may be a possible fault trace, and is reflected as a sharp rise in the terraces that run parallel to State Highway1 (1955 Aerial Photo Series).

***Figure 2.12 - Convergence of Potentiometric Contours Towards the Amberley Structure***



alternated between braided and meandering morphologies as they crossed actively growing folds and areas of subsidence. In situations where the river does not have sufficient energy to maintain lateral planation, the river begins to incise the underlying surface, abandoning previous strath surfaces (Campbell and Yousif, 1987). Cycles of aggradation and degradation during glacial and interglacial periods, combined with periods of uplift and deformation resulted in a complex depositional history. Subsequent shifting of channel courses resulted in channel abandonment of more permeable-well sorted units that were buried during periods of aggradation. The net result is numerous cross-cutting cut-and-fill reworked deposits, forming discrete permeable channels exhibiting a higher permeability than the surrounding sediments, and therefore, act as preferred paths for groundwater flow.

Initial attempts to correlate the strata and aquifers through cross-sections of stratigraphic logs (B-1) proved to be difficult as the spatial distribution of lithologic units and aquifer thickness thicknesses vary over small distances, as shown in Figure 2.13. The wells presented in the figure are located within a 500-metre radius of one another. Based on the depositional and structural development of the basin, and evaluation of lithologic logs from groundwater wells, it is concluded that the Waipara hydrogeological system consists of discrete buried river channels and water-bearing units. A conceptualised model of the hydrogeological system of the Waipara Basin is presented in Figure 2.14. Formations represented in the model include basement (Torlesse and Tertiary), Kowai Gravels (brown), Teviotdale Gravels (beige), and the Canterbury Gravels (yellow).

Light blue channels included in the Teviotdale and Kowai Formation represent the ancestral abandoned river channels, which have subsequently been filled in by aggradation events. The relatively permeable buried alluvial channels presently form the aquifers of the Waipara basin, and provide a significant water resource for the region. The aquifers included in the Kowai Formation are depicted as thicker and more laterally extensive aquifers since they are believed to have been more uniformly distributed throughout the region and did not experience as many cycles of aggradation and degradation like the Teviotdale, waipara and omihi gravels (Canterbury Gravels).

***Figure 2.13 - Stratigraphic Cross-section of a Suite of Wells along Georges Road, Waipara Illustrating the Geologic Heterogeneity and Variability in Aquifer Thickness***

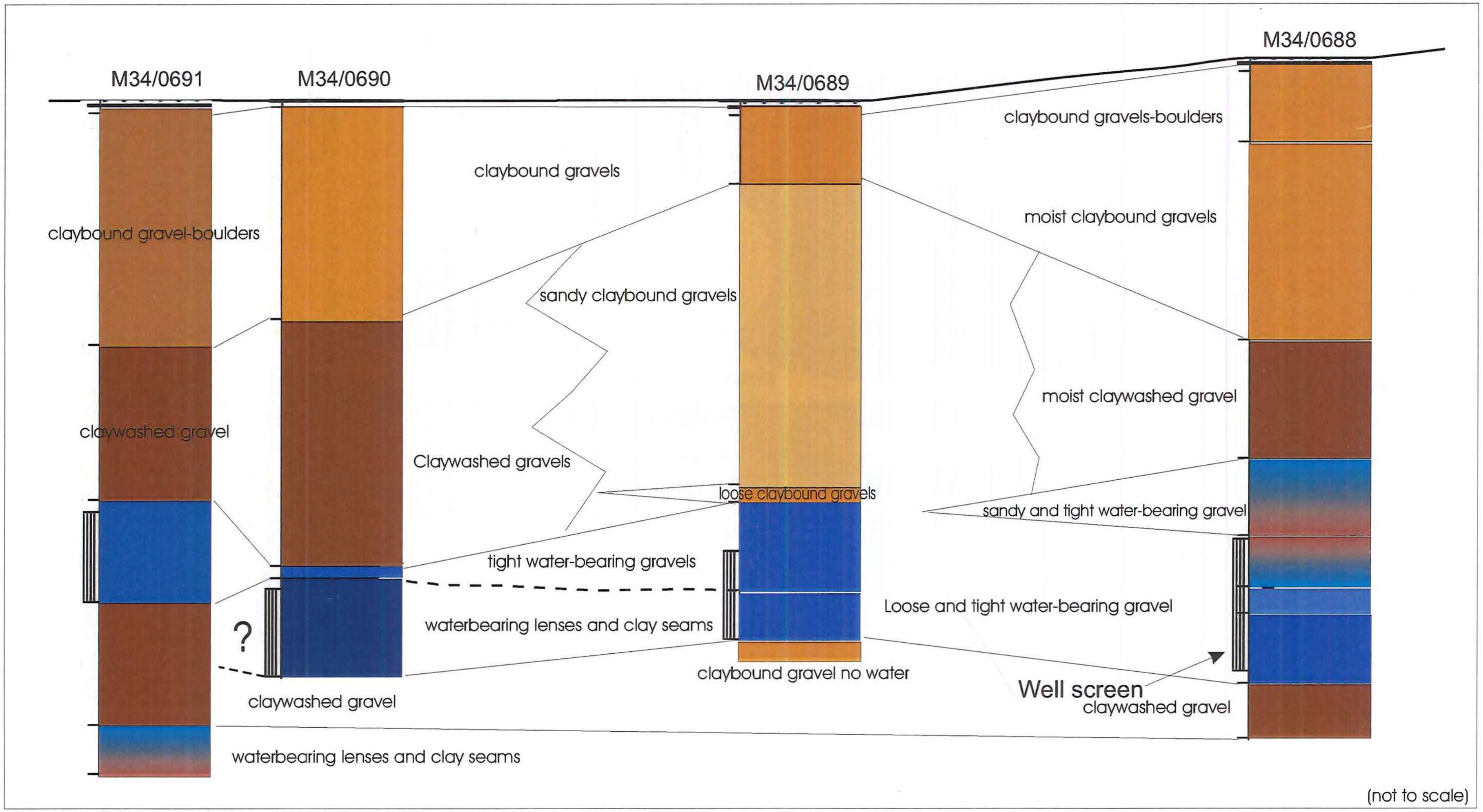
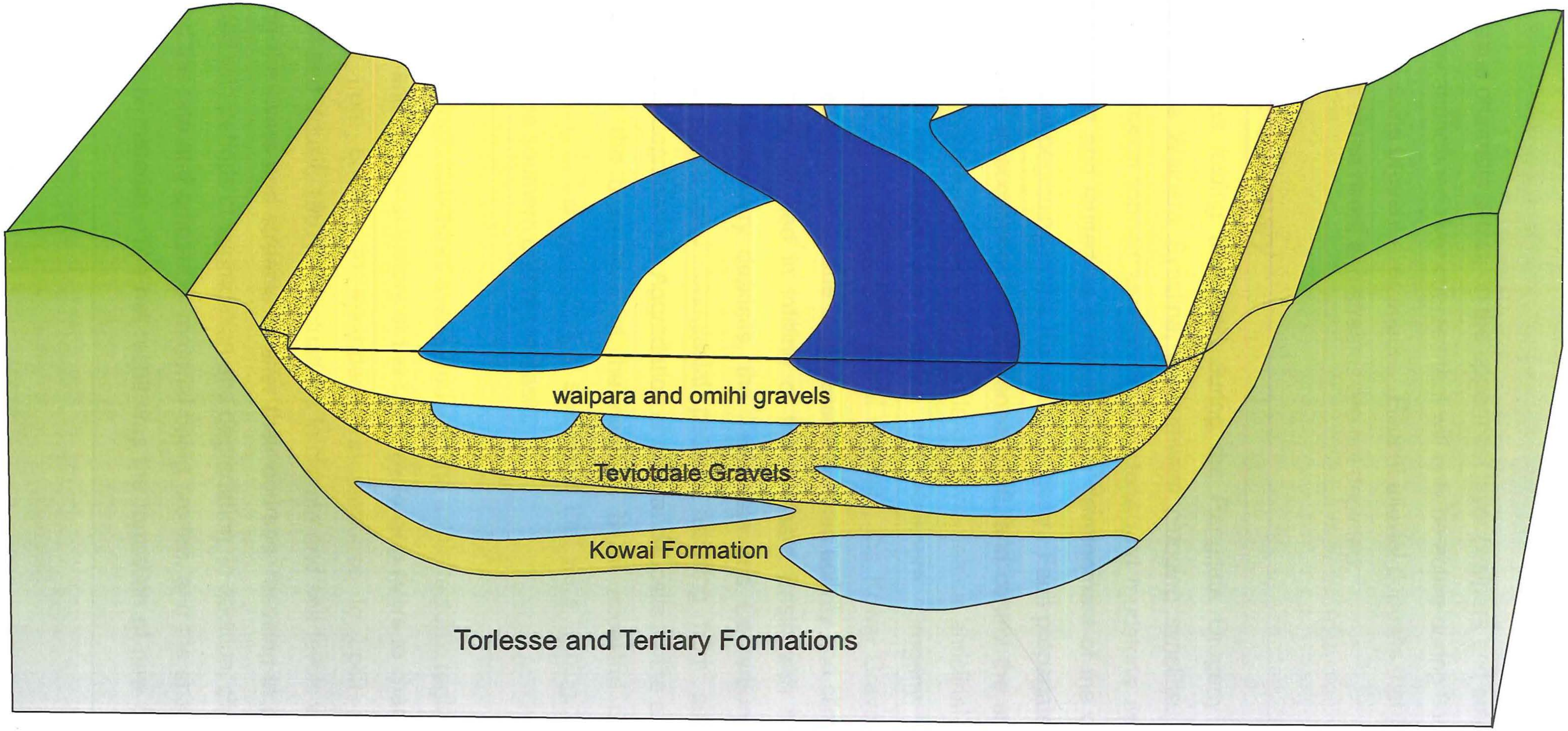


***Figure 2.14 - Simplified Conceptual Model of the Development of the Hydrogeology of the Waipara Alluvial Basin***



The light blue channels shown on the uppermost layer (waipara and omihi gravels) are modern day abandoned river courses that will only be active during flooding. The dark blue channel is the present river course. Recent alluvial deposits that form the modern day floodplains of the rivers and streams are not depicted.

## 2.6 Chapter Summary

Early Cretaceous folding and uplift during the Rangitata Orogeny resulted in the formation of the Waipara Syncline, a southwest plunging syncline. In the Tertiary, marine transgression formed sandstone, limestone and mudstone sequences, which were later folded and faulted as a result of the development of the convergent plate boundary and the beginning of the Kaikoura Orogeny. Fault propagated reverse/thrust faults developed to accommodate differential uplift, and control the structural grain of the basin, forming narrow basins between large asymmetrical anticlinal folds. Uplift and erosion of the Southern Alps during the Kaikoura Orogeny produced thick accumulations of Early Pleistocene fluvial deposits, the Kowai Gravels. Accelerated erosion of topographic highs due to increased tectonic activity and climatic fluctuations in the Quaternary resulted in infilling of the Waipara Basin with massive quantity gravels. Late Quaternary deposits, the Teviotdale and Canterbury Gravels, were formed during glacial and interglacial periods resulting from several cycles of aggradation and degradation. Aggradation of alluvial deposits by the ancestral Waipara River controlled the base level of the northern basin ancestral rivers and major tributaries resulting in the deposition of sediments that were lithologically distinct from the material in the southern part of the basin.

Subsurface geologic structures associated with the active tectonic regime influenced the depositional and erosional history of the basin by forcing rivers to change their channel morphology from braided to meandering in response to uplift and deformation (Campbell and Yousif, 1987). Fluctuations in climate and sea levels were instrumental in forcing the rivers and streams to alter their courses, resulting in cycles cut-and-fill associated with periods of aggradation and degradation. In addition, climatic fluctuations controlled the rate and amount of material being eroded, and the spatial distribution of the depositional material. The net result was the formation of new channels and the abandonment of old ones. The changing depositional environment prevented the development of laterally continuous, well sorted, permeable aquifers. The hydrogeology of the Waipara Basin consists of aquifers resulting from numerous cut and fill cycles formed during periods of aggradation and degradation of the land surface forming discrete channels, and semi-permeable lenses that are geologically heterogeneous and of variable thickness.

# CHAPTER THREE
# GEOPHYSICAL INVESTIGATIONS

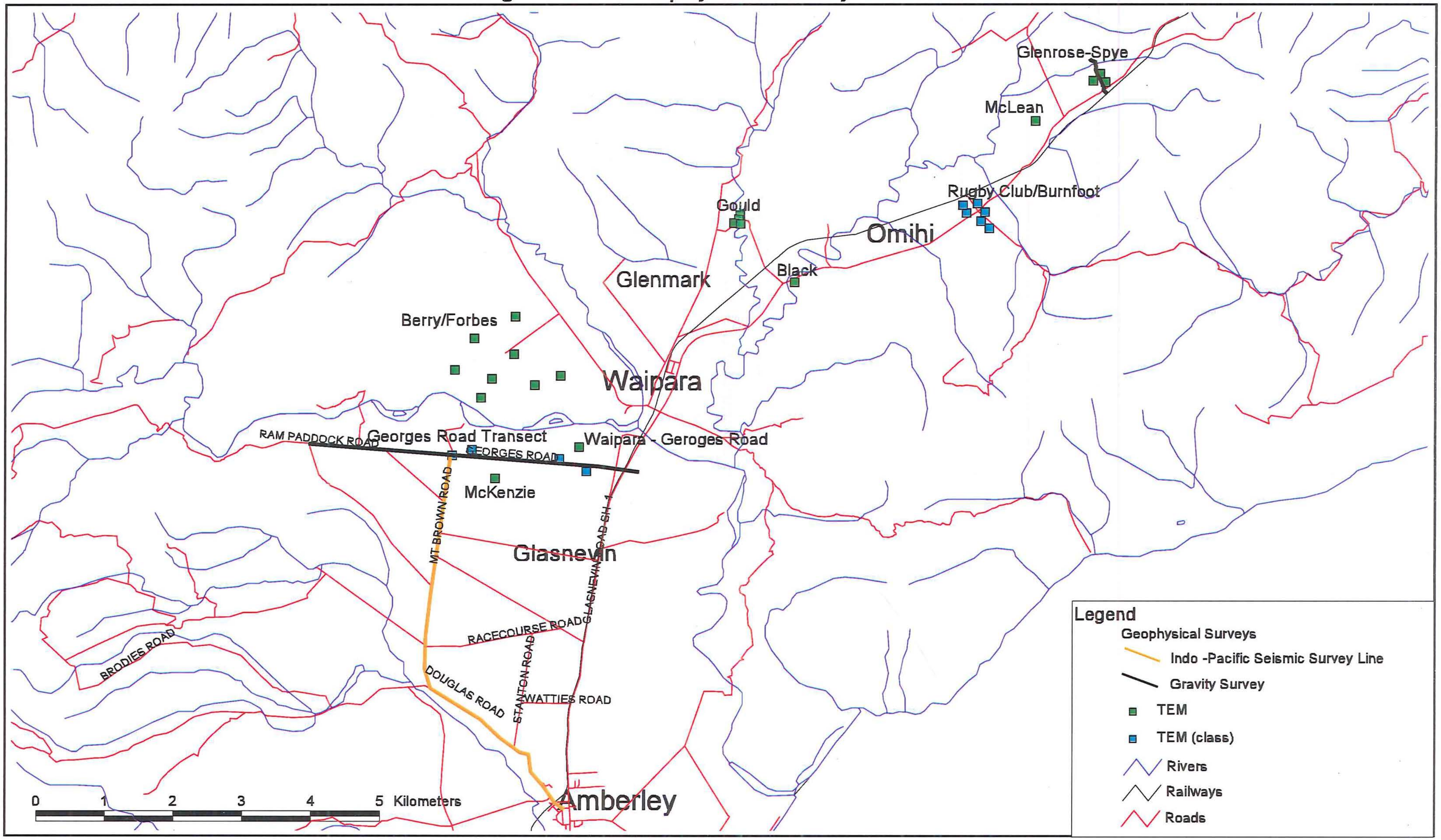
## *3.1 Geophysical Survey Objectives*

Geophysical methods used in this study include gravity and transient electromagnetic (TEM) methods. Gravity surveys were used to constrain the depth to Torlesse basement and Tertiary sequences, to determine the basement topography, and to provide an estimate of the thickness of the alluvial cover deposits. TEM surveys were employed in an attempt to identify and map aquifers, and delineate structural features that may affect the hydrogeology, and to assess the merits of using TEM methods for groundwater exploration in the Waipara alluvial basin.

The use of gravity methods for this purpose has been well documented (Kearey and Brooks, 1984; Telford et al., 1990;). Transient or time-domain electromagnetic (TEM/TDEM) methods have been successfully employed in many regions all over the world for locating and mapping aquifers because TEM methods are capable of resolving conductive layers that may have higher water content (Fitterman et al., 1986; Fitterman, 1987; McNeill, 1990). In addition, the signal generated by the TEM method is capable of penetrating the subsurface to depths of up to 200 metres. However, the depth of penetration is highly dependent on the properties of the transmitting medium, and the expected depth of penetration of the TEM signal in North Canterbury gravels is estimated to be approximately 100+ metres (D. Nobes and M. Armstrong, pers.comm.,1999). The TEM method was chosen because of the expected depth of penetration of the TEM signal, the TEM method is inexpensive, the data can be processed relatively quickly, and surveys can be completed, if necessary, by one person.

Prior to this study, only 1 geophysical survey had been completed in the study area. In the late 1960's, Indo Pacific completed a seismic survey extending from Douglas Road to the intersection of Mt Brown Road and Georges Road (Figure 3.1). The resolution is poor by modern standards (M. Finnemore, J.K. Campbell, pers. comm., 1999), and was unavailable for further interpretation. Re-interpretation of the Indo-Pacific seismic line

*Figure 3.1 - Geophysical Survey Locations*



was completed in 1999 by Richard Jongens, and was used to generate the geologic map presented in this study (Figure 1.3a, pocket).

Site locations of all surveys are shown in Figure 3.1. TEM surveys were completed in locations where bore logs were available for correlation with geophysical data and results. Portions of geophysical data and results presented in this study were collected and processed by the University of Canterbury's 1999 Fourth Year Geophysics Class.

## 3.2 Gravity

### 3.2.1 Gravity Theory

The gravity method is one of the most commonly used methods for mapping the depth to basement and associated topographic features (Kearey and Brooks, 1984; Telford et al., 1990). The gravity method works by responding to density (mass per unit volume) contrasts between geologic units and is based on Newton's laws of gravitational attraction and acceleration. The strength of the attraction between two bodies depends on the mass of the bodies and the distance between them. Newton's first law of gravity states that the gravitational attraction ($F$) between two bodies of mass ($m_1$ and $m_2$) is a function of the relative distance between them ($r^2$) and the gravitational constant ($G$), which has a value of 6.672 x $10^{-11}$ N $m^2/kg^2$:

$$\boxed{F = G(m_1\, m_2 / r^2)} \qquad [3.1]$$

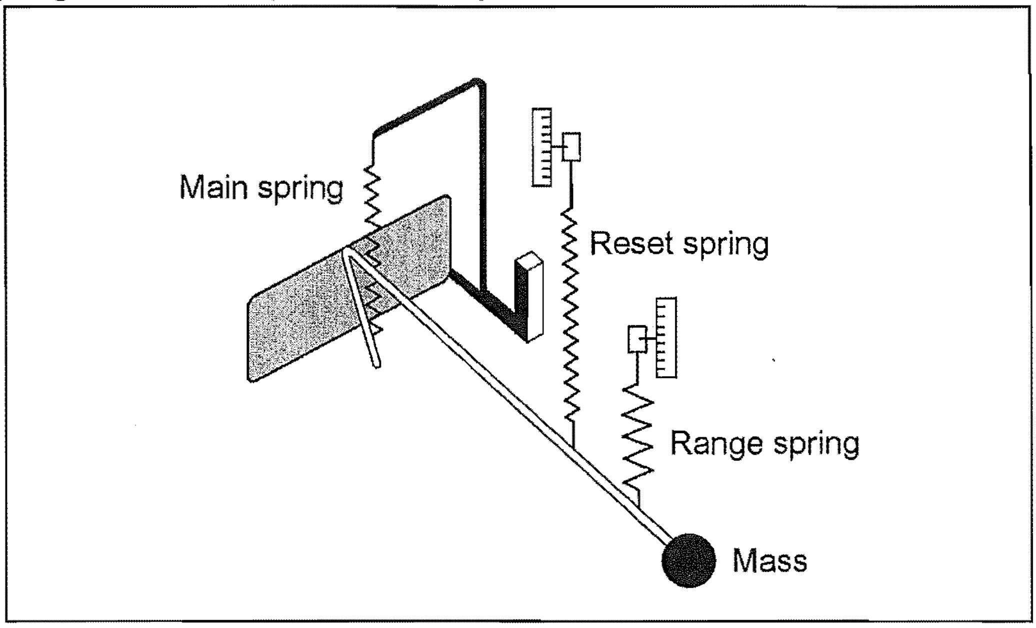
Therefore, the acceleration of an object with a given mass ($m_2$) at the surface of the Earth can be expressed as (Hinze, 1990):

$$\boxed{g = F/m_2 = G(M_E/R_E^2)} \qquad [3.2]$$

where $M_E$ is the mass of the Earth, and $R_E$ is the radius of the Earth. The unit measurement of the acceleration of gravity ($g$) is the *gal*, and is equal to 1 cm/sec$^2$. Gravity anomalies are expressed in milligals (mGals), which is approximately equal to 1 part per million (ppm) of the gravitational acceleration at the surface of the Earth.

Gravity survey methods employ an instrument called the gravimeter (Figure 3.2). A unit mass is connected to a highly sensitive crystal spring (the range spring), and a main "zero-length" spring which is connected to the arm with the unit mass, providing constant and equal support. This enables the range spring to respond to small changes in the gravitational pull being exerted on the mass unit by the mass of the Earth ($M_E$) at different locations on the Earth's surface ($R_E^2$). The changes in the density of the underlying local geologic units at different locations are reflected in changes in gravity measurements.

***Figure 3.2- Schematic Illustration of the Worden Gravimeter. Measurements are made by restoring the mass back to a standard position by adjusting the reset spring with the dial (Parasnis, 1986).***




### *3.2.2 Gravity Methodology*

*3.2.2.1* *Field Methods*

Gravity surveys were completed with a Worden Gravimeter from Otago University. Data collected from two gravity surveys are presented. Survey spacings were determined based on the objective of the investigation, and the size of the survey area. Each survey line included a base station at which measurements were repeated approximately every hour in order to account for variations in the Earth's gravity field over time and the effects of instrument drift. At each survey station, two readings were made. Additional readings were made when discrepancies between readings were greater than 1 gravity meter unit, which is equivalent to 0.090 mGal. Gravity stations were located by use of a global positioning satellite (GPS) device and station elevations were surveyed with an EDM automatic levelling instrument.

*3.2.2.2 Gravity Variations and Data Corrections*

Gravity measurements are primarily affected by topography and geographical position. Corrections are made for variations in the Earth's gravity field, latitude and elevation of the survey stations, local and regional topography. Gravity corrections reduce the raw gravity measurements to a common datum, or equipotential surface such as sea level.

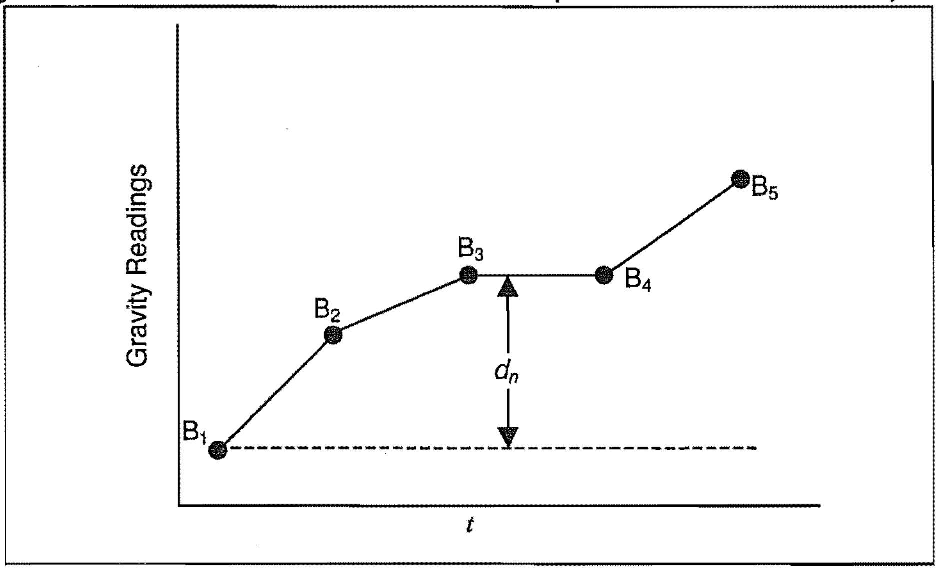
Large-scale and local variations in the Earth's gravity field occur because the speed at which the Earth's surface rotates is faster at the equator and the Earth is not perfectly spherical. Because of these two factors, variations in the Earth's gravitational field from the poles to the equator are estimated to be approximately 5000 mGals (1 mGal = $10^{-5}$ m/sec$^2$). Variations in the Earth's gravitational field occur with increasing distance away from the Earth's centre of mass. The resulting gravity readings reflect the gravitational forces associated with changes in latitude, and rotational effects of the Earth. In addition, local and regional variations in topography are superimposed on the observed gravity. However, if the elevation and latitude for a given gravity survey are constant, , then the variations are negligible. Base stations were established for each survey to correct for diurnal variations in the gravity field (i.e. earth tidal effects) and for instrument drift that is influenced by changes in temperature causing changes in the spring response over long time periods.

Prior to gravity variation corrections, gravity measurements (dial readings) were converted to milligals by a factor of 0.08905, specific to the instrument. Gravity data calculations and corrections were completed in Microsoft Excel spreadsheet.

3.2.2.2.1 Drift Correction

Temporal variations occur as a result of earth tidal influences and variations within the instrument during the surveys. In order to account for these variations, base stations were used. Base station readings were taken approximately every hour. The resulting drift between station readings is assumed to be linear, and therefore a rate of drift (mGals/min) can be established. The rate of drift (*d)* is calculated by determining the difference between two measured stations ($B_n$), and dividing the difference by the time (minutes) passed between the station readings as shown in Figure 3.3. This will result in an initial base station reading of zero ($B_1$) and a final reading equal to the total drift ($B_5$). The rate of drift between base station readings ($d_n$) is then added or subtracted to the observed measurements. If the following base station reading is higher, the difference is subtracted, and if lower it is added.

***Figure 3.3 – Base Station Drift Correction (modified from Parasnis, 1986)***




3.2.2.2.2 Latitude Variations

The gravitational pull of the Earth increases with geographical latitude and therefore, the data must be corrected for these variations. Latitude corrections were made by estimating the latitude at each station from the NZMS 260-M34 and 260-N34 1:50,000 topographic maps. In addition, all stations were located with a Trimble global positioning satellite (GPS) instrument with an estimated accuracy of 20 metres. The latitude correction is calculated by determining the net change in latitude of each station along the line relative to an arbitrarily chosen gravity station, and multiplying it by a constant as shown in the following equation:

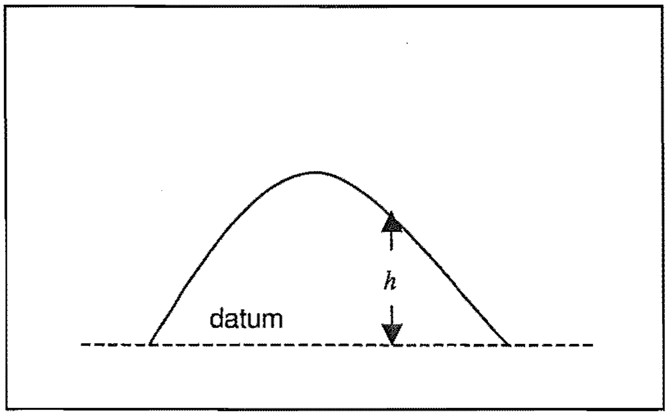
$$\boxed{\Delta g_{latitide} = \Delta g_{measured} + 0.811 \sin 2L \ \ mGal/km} \qquad [3.3]$$

where L = latitude. The resulting value is then added to the measured gravity reading if north of the reference station, and subtracted if south of the reference station.

3.2.2.2.3 Free Air Correction (First Order Elevation effects)

The observed gravity reading will be due in part to the height of the gravity station above sea level. The free-air correction (Figure 3.4) accounts for the changes in distance from the centre of the Earth between stations by reducing the measured

***Figure 3.4 – Free-Air Correction (modified from Parasnis, 1986)***




readings to a common datum (i.e. elevation above sea level). With increasing distance from the centre of the Earth, the observed gravitational effect (*g*) decreases at the surface of the Earth at a rate of 0.3086 mGal/m, and therefore the observed data needs to be corrected as shown in the following equation:

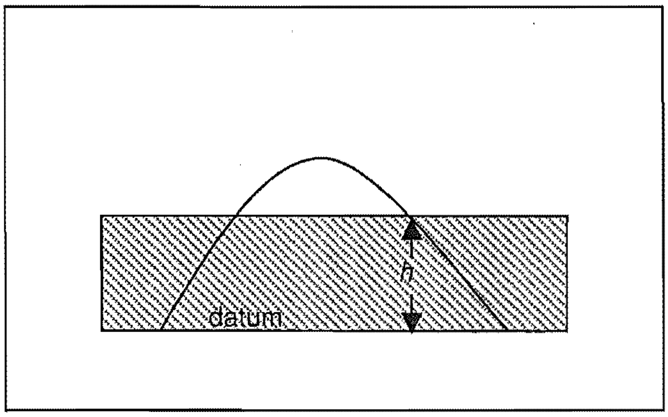
$$\boxed{\Delta g_{FA} = \Delta g_{latitude} + 0.3086\ h \ \ mGal/m} \qquad [3.4]$$

where *h* is the station elevation (metres) above sea level. For elevations above sea level the value is added, and subtracted for elevations below the common datum. Elevations were established by surveying each station from a known benchmark.

3.2.2.2.4 Bouguer Correction (Mass effects)

The Bouguer correction accounts for the gravitational attraction that is exerted by the material between the horizontal plane of each station and the datum plane, which was ignored by the free-air correction (Figure 3.5). The Bouguer correction assumes the existence of an infinite slab of material with a specific density. For this study, a density of 2670 kg/m$^3$ for greywacke was assumed. The elevation of each station relative to a common datum is calculated, and multiplied by the slab density and by a constant. The Bouguer

***Figure 3.5 – Bouguer Correction (modified from Parasnis, 1986)***




correction is always negative except when below sea level:

$$\boxed{\Delta g_{bouguer} = \Delta g_{FA} - 0.04192\,\rho h \;\; mGal/m} \qquad [3.5a]$$

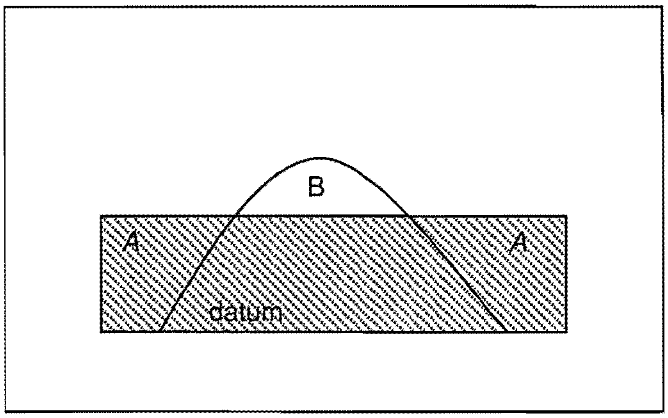
where ρ is the slab density (kg/m$^3$). Assuming an average crustal density of 2670 kg/m$^3$ the equation becomes:

$$\boxed{\Delta g_{bouguer} = \Delta g_{FA} - 0.112\, h \;\; mGal/m} \qquad [3.5b]$$

3.2.2.2.5 Terrain Corrections

Terrain corrections correct for the local topographic relief in the vicinity of the gravity stations (Kearey and Brooks, 1991) that are not accounted for by the Bouguer correction (Figure 3.6). The regions designated A in Figure 3.6 are included in the Bouguer correction, however, they do not consist of rock, and the Bouguer correction has overcompensated for these areas. The area designated B consists of rock, and is not included in the Bouguer correction. The area designated B exerts an upward component of gravitational attraction resulting in a lower observed gravity reading, which requires further correction.

***Figure 3.6 – Terrain Corrections (modified from Parasnis, 1986)***




Terrain corrections were completed by use of Hammer charts (Hammer, 1945). The Hammer chart is a transparent circular chart, which is divided into radial and concentric compartments representing varying distances from the gravity station (Appendix C-1). The chart is overlain on a topographic map at the gravity station locality, and the average topographic elevation for each compartment is determined. The elevation of the gravity station is subtracted from the average compartment elevation, and the average gravitational effect is determined from a set of corresponding reference tables (Appendix C-1). The total terrain correction is then calculated by summing the gravitational effects contributed from each of the compartments.

Records of topographic variations were kept during the surveys, and were used for determining the inner terrain corrections. Outer terrain corrections were made by separating each compartment into quarters, estimating the average elevation in each quarter. Corrections were carried out for compartments B through I. All terrain corrections are added to the measured gravity value.

3.2.2.2.6 <u>Regional Trends</u>

Regional trends were estimated from the NZGS 1:250,000 Sheet 18 Bouguer Anomaly Map. Regional trends are added to the measured gravity value when the trend is decreasing and subtracted when the regional trend increases across the survey line. For both gravity surveys completed during this study, the regional trend increased from east to west.

#### *3.2.2.3 Variations and Errors Associated with Gravity Measurements*

There are several factors that contribute to variations in gravity data. The most significant errors are introduced during the levelling of the instrument and adjusting the nulling screw while taking measurements. Multiple readings were made at each station to reduce measurement errors. Environmental effects such as wind and traffic can cause the spring in the instrument to vibrate, and result in measurement errors. However, vibrational effects were not significant as surveys were carried out on rural roads away from heavy traffic conditions. For stations that were close to high traffic roads, measurements were made intermittently between passing traffic. Weather conditions during each of the surveys were fine with minimal wind effects.

Additional errors result from gravity corrections when estimating relative latitude changes, elevations, and topography. Latitudes were estimated from a 1:50,000 topographic map and use of a Trimble GPS instrument. Surveying each station using the EDM Automatic level with a triple prism reduced errors in elevation estimations. Changes in topography near a gravity station were recorded during the surveys to aid in those corrections, thereby reducing the error in the corrections. In addition, topographic features suspected to have an effect on gravity measurements were surveyed with the EDM survey equipment. After all the corrections have been applied can the data be modelled, as only the final corrected data are truly representative of the relative density contrasts of the underlying geologic units.

### 3.2.3 Glenrose Gravity Survey

#### *3.2.3.1 Survey Design*

The Glenrose-Spye survey is located at the northern limits of the field area (Figure 3.1). The objectives of the Glenrose-Spye gravity survey were to constrain the location of the

Omihi Fault, and determine depth to basement. The survey extended for approximately 900 metres along the Baxter driveway, across SH1 to Spye (Figure 3.7). Stations were spaced approximately 100 metres apart (including the base station), and base station readings were recorded every hour. The Glenrose gravity survey was completed with the assistance of Stefan Charteris, formerly of Environment Canterbury. For each station, a total of four alternating measurements were made. Readings were repeated when there were significant deviations. Changes in the local topography were recorded during the survey.

#### *3.2.3.2 Data and Corrections*

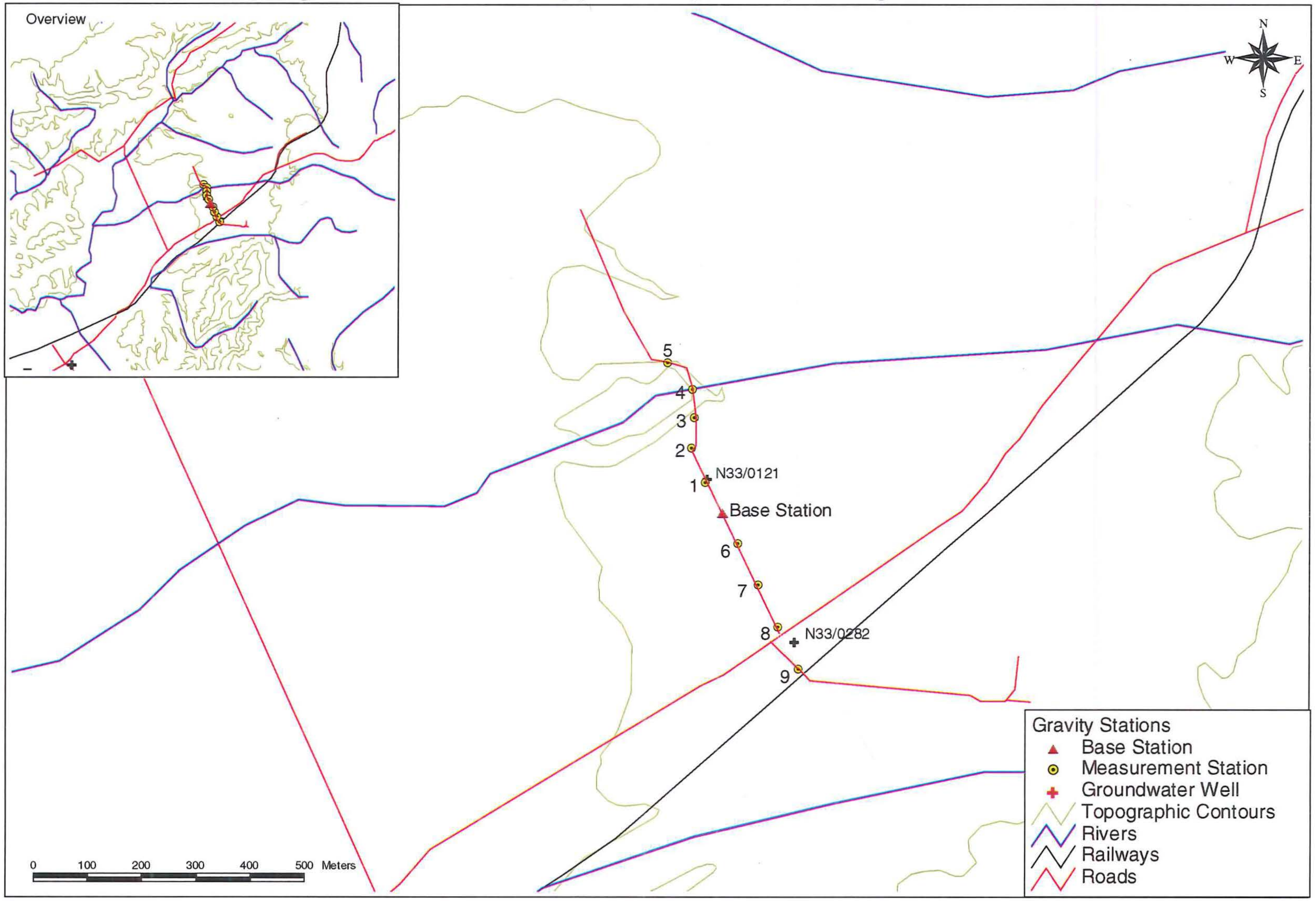
All Glenrose-Spye gravity data and corrections are presented in Appendix C-2. Corrections for local terrain effects were completed for stations S5, the base station, and S9 because they were the stations most likely to be affected by the local topography. This indicates that the local terrain effects affected all the stations approximately equally, and therefore, local terrain corrections were not applied. All data were corrected for drift, latitude, elevation (free-air) and mass effects (Bouguer), and regional trends.

#### *3.2.3.3 Results and Interpretation*

The total change in milligals along the survey line is 1.2 mGals, with the greatest anomaly occurring between stations S4 and S3 (Appendix C-1). Corrected gravity data were modelled using the gravity modelling program GM-SYS, in order to constrain depth to bedrock and identify structural features. GM-SYS utilises the observed gravity data to calculate the best-fit curve in order to determine the error associated with the respective model. The models are formulated based on the number of layers input, the assigned densities of the layers, and the geometry and structure of subsurface topography. The generation of an accurate model therefore, requires some knowledge of the density of the underlying material, and knowledge of the subsurface geological structure and stratigraphy.

A three-layer model was chosen to represent the Torlesse greywacke (bedrock), the Tertiary marine sequence composed of limestones, siltstones and sandstones, and the

## Figure 3.7 - Glenrose-Spye Gravity Survey Configuration



unconsolidated Pliocene/Pleistocene marine and alluvial deposits. Geologic mapping by Wilson (1963) and others provided some constraint on the thickness and structure of the underlying geology. Approximately 1400 metres east of the survey line the Tertiary sequences have been uplifted and faulted, which provided some structural control for modelling the gravity data. In addition, 50 metres north of the survey (Figure 3.7) there is a 170 metre bore, which confirms that the gravel thickness is at least 200 metres at the eastern end of the survey line.

Suggested density values for various rock types are shown in Table 3.1 (Telford et al., 1990). A variety of density values were used to determine the best-fit model. Different density values had minimal effects on the overall structural geometry and

***Table 3.1 - Suggested Densities for Various Rock Types. Average densities are in parentheses (modified from Telford et al., 1990).***

| Rock Type | Density ($kg/m^3$) Wet | Dry |
|---|---|---|
| Alluvium and sediments | 1960 – 2000 | 1500 – 1600 |
| Clay | | 1630 – 2600 (2210) |
| Sand | | 1700 –2300 (2000) |
| Gravel | 1700 - 2400 | 1400 – 2200 (2000) |
| Sandstones | 1610 - 2760 | 1600 – 2680 (2350) |
| Limestones | 1930 - 2900 | 1740 – 2760 (2550) |
| Shale | | 1770 – 3200 (2400) |
| Greywacke | | 2600 – 2700 (2650) |

thickness of the layers. The density parameters that produced the best-fit model included 1800 $kg/m^3$ for the cover deposits, 2400 $kg/m^3$ for the Tertiary marine sequences and 2670 $kg/m^3$ for the Torlesse basement greywacke. Figure 3.8 shows the best-fit model for the Glenrose-Spye gravity survey. The curve-fitting error was minimal (0.163 mGal). Other models produced slightly higher errors. Models generated with alternative density input values are presented in Appendix C-3.

Estimated thicknesses and formation depths from the best-fit model correlates well with the subsurface interpretations by Wilson (1963). Depth to Torlesse basement is estimated to be 1000 metres. The thickness of the cover deposits range from 300 metres at the eastern end of the survey line to 400 metres to the west. The thinnest portion of the cover deposits is approximately 150 metres, and is located between stations S2 and S3.

Modelled data suggests the presence of an anticline towards the western end of the survey between stations S2 and S3. Interestingly, several springs discharge in the area between these two stations. Figure 3.8 shows a structural interpretation of the gravity model illustrating an eastward verging reverse fault propagating at depth to form an asymmetrical anticline. The structural interpretation is based on previous geologic mapping and structural interpretation of North Canterbury structural styles, which suggests that many of the anticlinal folds are formed by concealed faults of this type (Yousif, 1987; Nicol, 1991; Campbell and Nicol, 1992; Nicol et al., 1994; Pettinga and Armstrong, 1998).

### 3.2.4 Georges Road Surveys: Data, Results and Interpretation

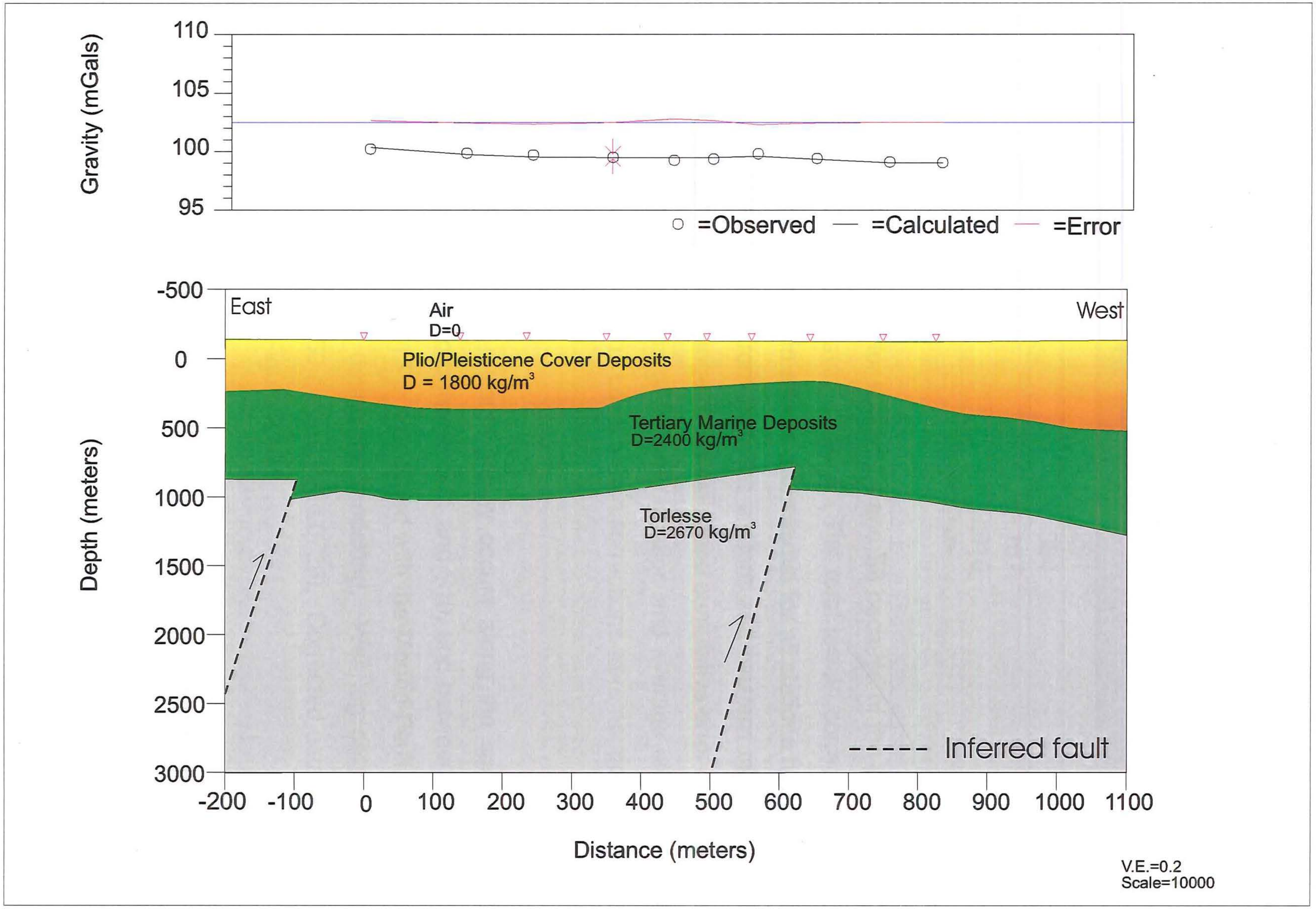
#### *3.2.4.1 Survey Design*

The Georges Road gravity survey extended for approximately 8500 metres from the intersection of Mound Road to the east side of State Highway 1 (Figure 3.9). The objectives of the gravity survey were to determine the depth to basement, thickness of overlying cover deposits, and map the fault associated with the Mound, as described by Nicol and others (1994). Stations were spaced approximately 400 metres apart, and base station readings were recorded every hour. Two readings were taken at each station, and additional readings were made when there were significant deviations. Changes in topography were recorded in the field.

#### *3.2.4.2 Gravity Data and Corrections*

The Georges Road Gravity data and corrections are included in Appendix C-4. Maximum deviation between readings at a given station was 0.8 mGals, and an overall average deviation of 0.1 mGal. All data were corrected for drift, latitude, elevation (free-air and Bouguer), and regional trends. Calculating the terrain corrections for gravity stations S1, S4, S6 and S25 assessed the effects of the local topography. The stations

***Figure 3.8 - Glenrose-Spye Gravity Model and Interpretation***



chosen represented those most likely to be affected by the local topography. Hammer chart terrain corrections for gravity stations S1, S4, S6 and S25 are included in Appendix C-4 and listed in Table 3.2.

***Table 3.2 – Total Terrain Corrections for Select Stations***

| Gravity Station | Calculated Total Terrain Correction (mGal) |
|---|---|
| S1 | .291 |
| S4 | .354 |
| S6 | .167 |
| S25 | .010 |

Terrain corrections were greatest for station S4 and S6 because of the presence of the ridge located just south of the gravity stations. The total terrain correction for S25 is .010, demonstrating that the terrain effects are minimal for all stations between S6 and S25, which are located furthest from both the eastern and western hills. Calculated terrain corrections fall within the range of the estimated cumulative error associated with gravity measurements, estimations of latitude, location and average elevation for 106 Hammer chart compartments (B-1). Local terrain corrections were not applied.

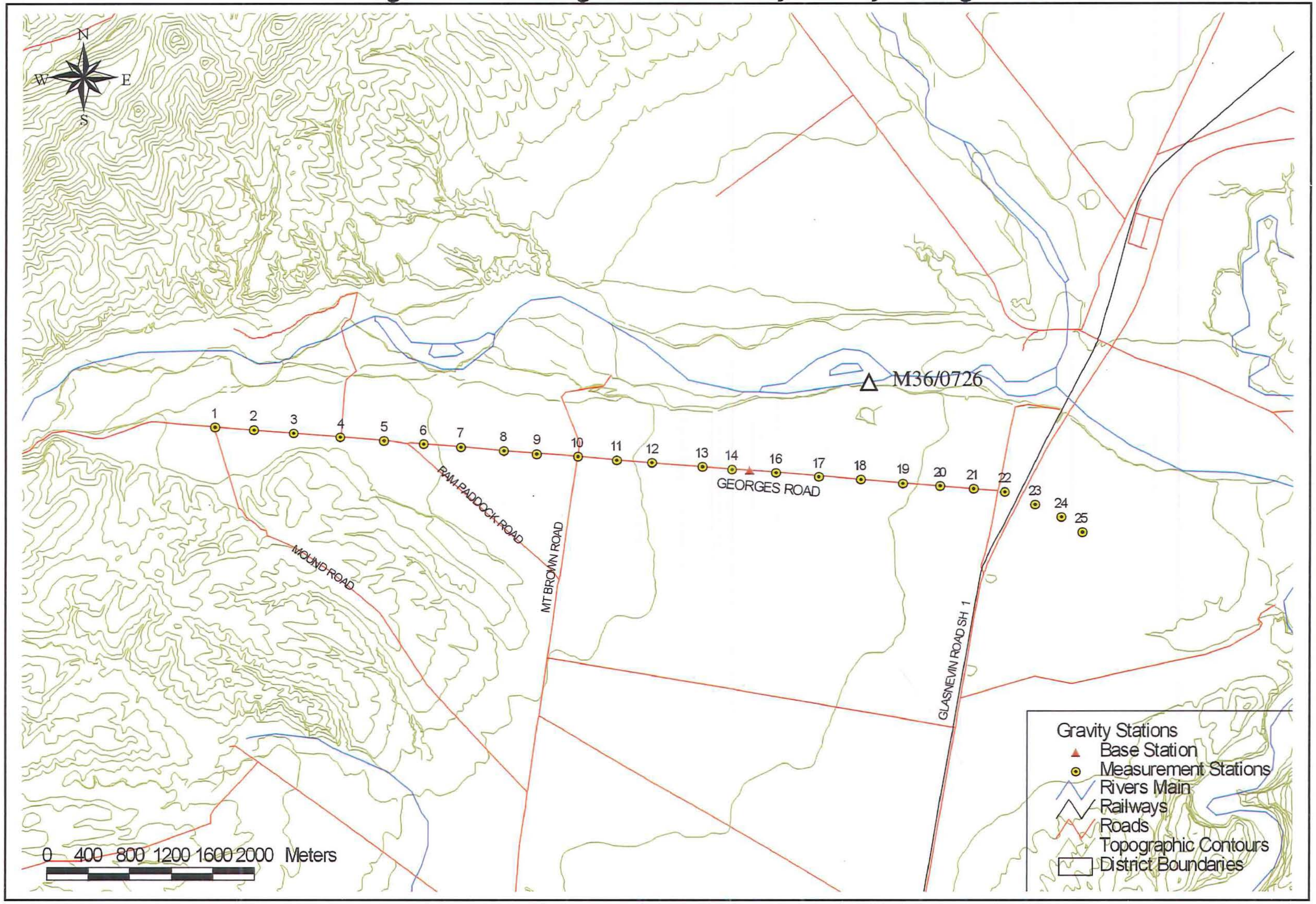
<u>*3.2.4.3 Results and Interpretation*</u>

A total change of 4.4 mGals in residual gravity occurs along the survey line. The greatest anomalies were observed between S11 and S10, and between S17 and S25. The anomaly between S17 and S19 is associated with the Mound Fault, and therefore, provided some structural control during the modelling. Well log data shows gravel thicknesses to be not less than 150 metres (M34/0726). Corrected data was modelled using GM-SYS and are shown in Figure 3.10.

The best-fit model was a three-layer model using a density of 1900 kg/m$^3$ for the cover deposits, 2400 kg/m$^3$ for the Tertiary sequences and 2670 kg/m$^3$ for the Torlesse basement layer. A variety of densities were input, however the densities listed above produced the lowest curve-fitting error of 0.230 mGals.

Based on the model, the thicknesses of the cover deposits range from 900 metres to

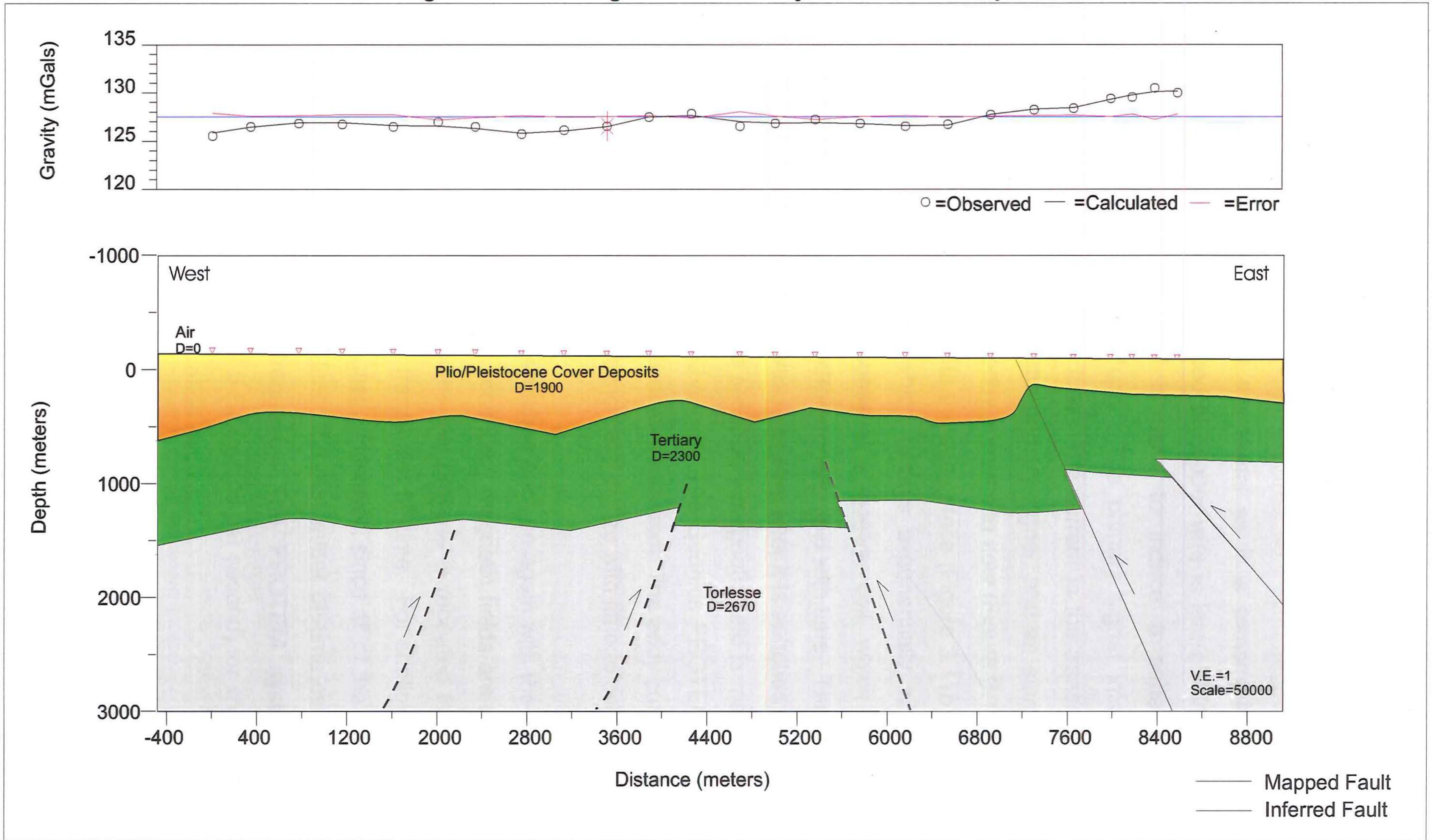
### Figure 3.9 – Georges Road Gravity Survey Configuration



250-300 metres. However, stratigraphic control is limited because the deepest well in the vicinity is M34/0726 (Figure 3.9), which is located on the lower terrace along Georges Road. The well penetrates and is 116 metres deep, or 132 metres below the upper terrace in which the gravity survey was completed. Samples collected during drilling at depths greater than 50 metres exhibited higher concentrations of quartz sands and Tertiary limestone, and are interpreted to be indicative of the Kowai. The last 5 – 10 metres of drilling penetrated water saturated fine and medium grained sands. No fossils were found in the samples and therefore, positive identification of the strata was not possible. Thus, constraints on the modelled thicknesses of the overlying alluvium are limited

The resulting model suggests that the basement topography is disrupted by faulting at depth, and is not as uniform as previous geologic models depicted. The anomalies at the eastern end of the survey line are attributed to eastward dipping reverse or thrust faults. The second most eastern anomaly has been identified and modelled after the Mound Fault discussed by Nicol (1994). The gravity data required the input of a second thrust to the east to produce the best-fit model. The anomalies and resulting subsurface anomalies to the west of the Mound fault have been interpreted as eastward verging thrusts resulting from the reactivation of older Cretaceous features, as observed in other regions in Northern Canterbury. The Boby's Creek Fault, an east-west striking strike-slip fault with dip-slip motion, propagates into the basin from the west (Figure 1.3a), and may be an influential feature in forming the thrusts modelled in Figure 3.10. However, the structural geometry and position of the Boby's Creek fault in the vicinity east of Mound Road is poorly understood. Modelling and interpretation of subsurface structural features expressed by the gravity anomalies is difficult without surface constraints or seismic data, and numerous interpretations can be applied.

***Figure 3.10 - Georges Road Gravity Model and Interpretation***



## *3.3 Transient or Time-Domain Electromagnetics*

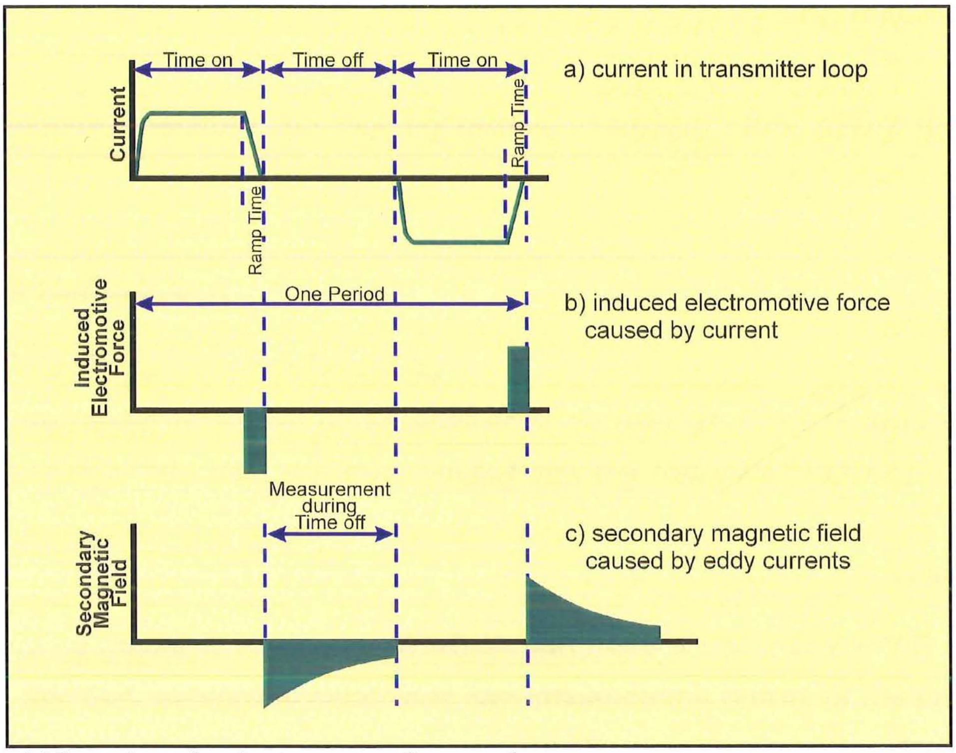
### 3.3.1 Transient Electromagnetic (TEM) Theory

Time-domain electromagnetic methods (TEM) generate an electromagnetic signal in the ground and measure the response of the signal as it is transmitted through the subsurface. A transmitter loop composed of copper wire is laid out in the form of a square on the ground surface, and is used to induce a series of transient electromagnetic signals in the subsurface. The primary signal interacts with the subsurface medium inducing current to flow. The current in the transmitter is rapidly shut off, resulting in the termination of the primary signal, and an electromotive force (emf) is induced in the ground causing eddy currents to flow (Figure 3.11a). The eddy currents propagate down and outward into the subsurface (Figure 3.11b), and generate a secondary electromagnetic signal, which decays exponentially with time. The resultant signal induces a current response at a receiver coil, which represents the decay (or strength) of the secondary electromagnetic field with time. The time taken for the current in the transmitter loop to decrease to zero after it is switched off is known as the *ramp time*. During the "off-time," the secondary magnetic field is measured (Figure 3.11a) in a series of time slices called channels. The Geonics PROTEM system used for the surveys has a total of 20 channels of measurement. The eddy currents decrease exponentially with time, and the channels increase in size with time to compensate.

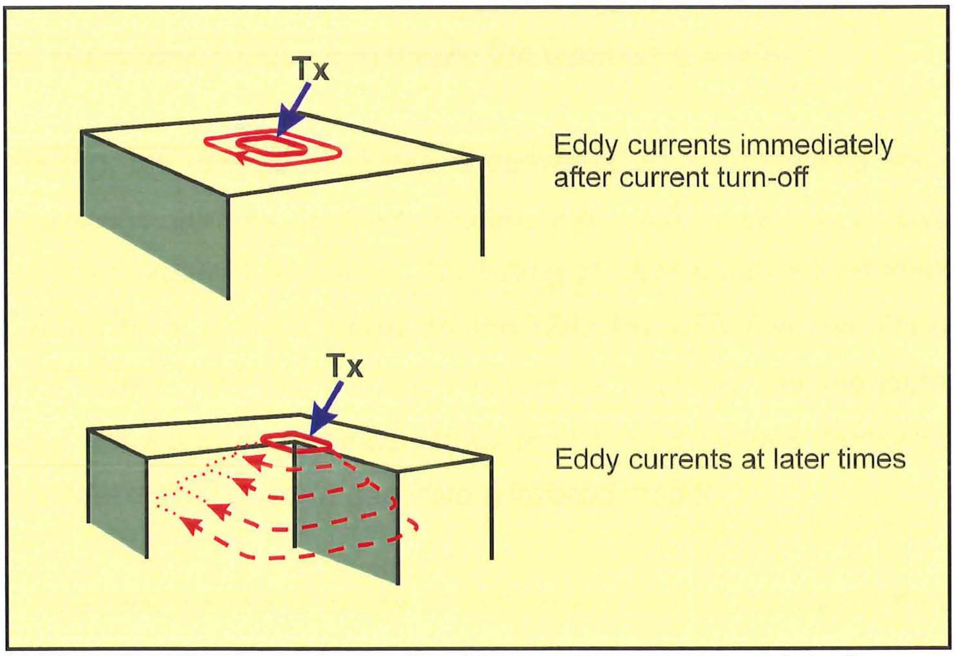
At the end of the off-time the current is switched back on again with the current flowing in the opposite direction. The resulting secondary magnetic fields are recorded in the subsequent off-time. The number of times this process is repeated is known as the *repetition rate*, and is dependent on the transmitter off-time. For shallower penetration depths, a shorter transmitter off-time is used. However, since all of the signal may not have decayed during that particular off-time, the transmitter off-time can be increased by selecting a different transmitter frequency. The PROTEM system uses four transmitter frequencies ranging from 237.5 Hz (cycles per second) for shallow depths of penetration, to 6.25 Hz for deeper penetration depths.

Because the size and propagation of the eddy current is a function of the subsurface electrical properties of the medium, the decay rate of the eddy current is a function of

***Figure 3.11 – Generation and propagation of Time-domain Electromagnetic Waveforms and Currents (adapted from McNeill, 1990).***




*a) Time-domain electromagnetic waveforms,*




*b) Time-domain electromagnetic eddy currents at early and late times* the conductivity of the subsurface geology. Measurement of the decay rate over time is a measurement of the conductivity with depth. Conductive materials result in a decrease in rate of decay as conductive materials attract the eddy currents, trapping the current, and providing preferred paths of propagation. Conversely, resistive materials readily transmit eddy currents, and therefore result in an increase in the decay rate. TEM techniques, therefore, resolve conductive materials more easily than resistive ones.

### 3.3.2 TEM Methodology

*3.3.2.1 Data Processing and Modelling*

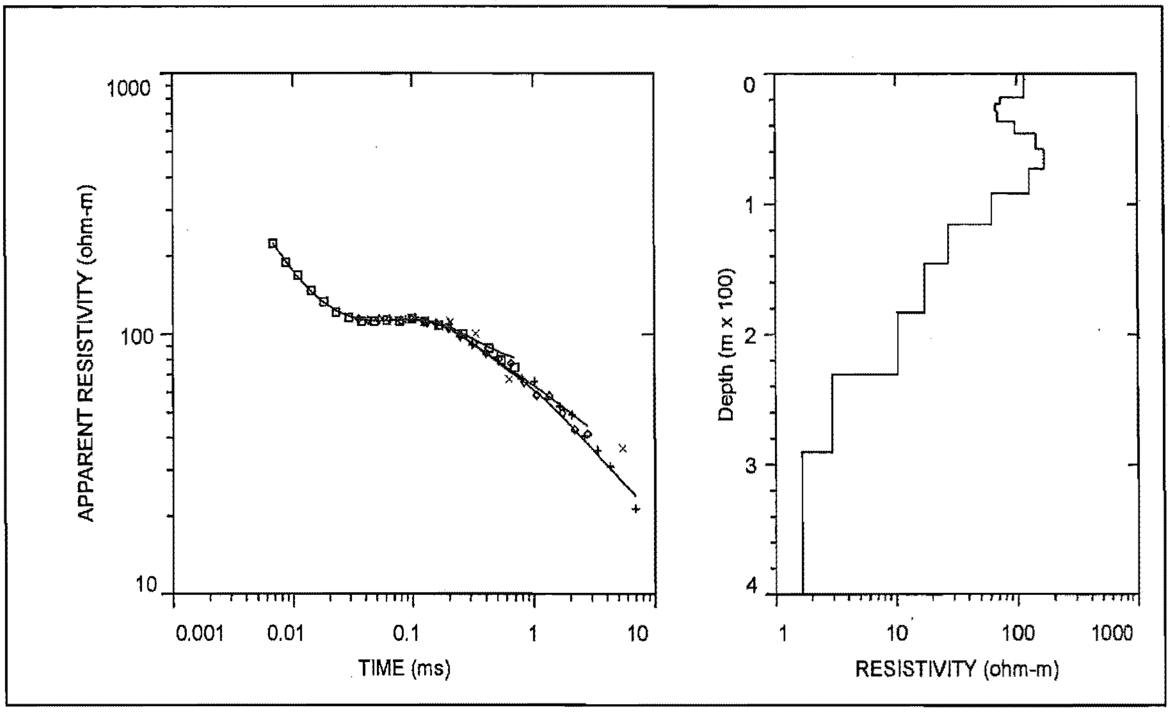
TEM data are stored in the PROTEM receiver in the field, and transferred to a computer in the laboratory. The data are then loaded into the Interpex TEMIX-GL™ modelling package during which the quality of the data is checked. TEM data of poor quality arise from both cultural and geological sources. Cultural effects include power lines, electric fences, farming machinery, etc., all of which can have a significant effect on the data quality. In addition, geological conditions can influence the quality of the data. In areas of high resistivity the signal dissipates so rapidly that there is insufficient time to measure it during the off-time. Conversely, in a highly conductive medium the signal gets trapped in the near surface and masks the underlying strata.

During modelling, the voltage response is converted to a normalized value called the *apparent resistivity*, and for a given model, the TEM response is calculated and compared to the measured response. Modelling of TEM data was initiated by allowing the computer to fit a smooth model to the data by adjusting the thicknesses and resistivities of layers until the modelled response matches the measured response (Figure 3.12). The apparent electrical structure of the subsurface medium produced by the smooth model is then used to generate a layered model.

Before a layer model is fitted, anomalous data points may be masked if they fall outside the trend set by the other data points. Data points that fall outside the trend are indicative of cultural and naturally produced noise levels as the signal decays over time (particularly at late times), and therefore is not representative of the natural response.

Masked data points are represented by an "x" on the plots of apparent resistivity versus time.

***Figure 3.12 – Example of a Smooth Model of TEM Data***

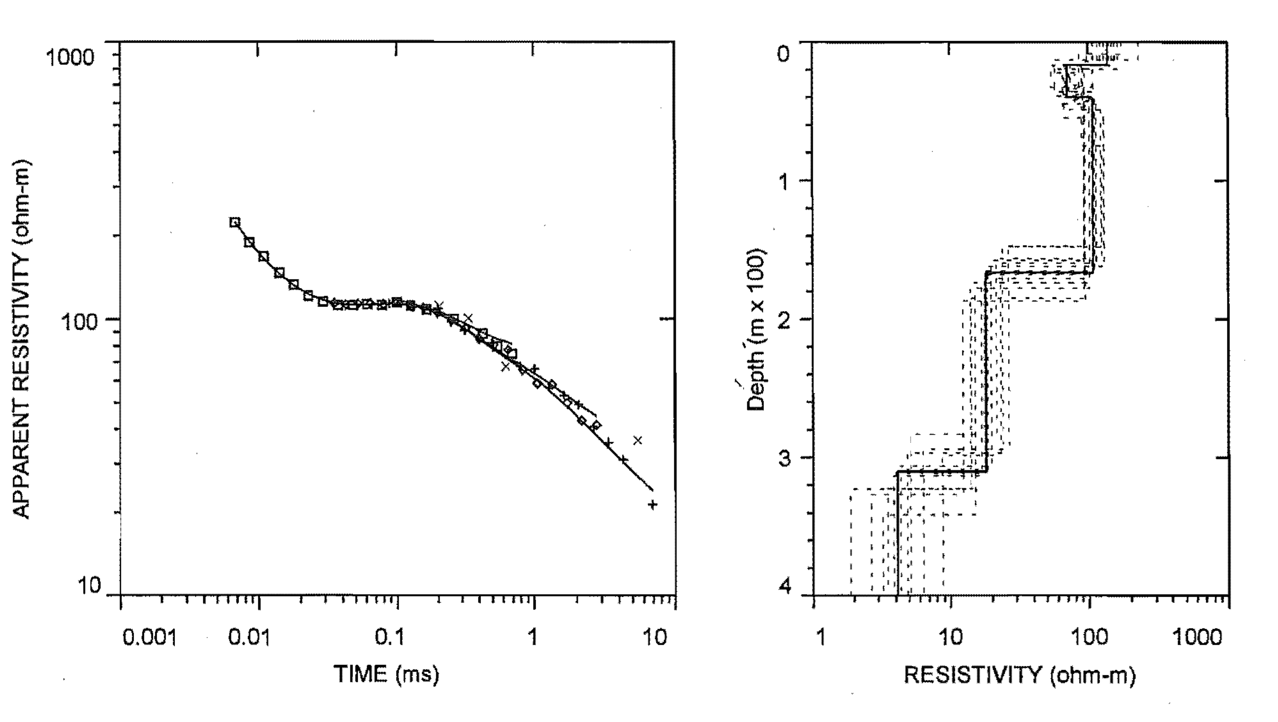



The "best-fit" layered model is generated by creating a starting model, which is then run through a computer "inversion" programme which calculates how the model layer resistivities and thicknesses should change to reduce the deviation between the measured and modelled responses. The best-fit model is established both by a manual fitting process, and by the computer through an iterative process, and additional layers can be added or removed as required to produce a calculated response that is in good agreement with the measured response. The deviation between the calculated and measured responses is determined, and the model is varied until a minimum deviation is achieved. Well-constrained models are indicated by fewer equivalence lines, and a smaller spread about the best-fit curve (solid line) as shown in Figure 3.13. Modelling of the TEM response helps to establish the electrical structure of the subsurface as a function of depth.

### *3.3.2.2 <u>Field Methods and Survey Design</u>*

TEM surveys were carried out using the "central loop" or "in-loop" configuration, which

***Figure 3.13 - Example of Equivalence Analysis.***




means that the receiver loop is placed at the centre of the transmitter loop. The loop size chosen for each survey was dependent upon the size of the survey area, the location of fences, power lines, and other objects that could affect the electromagnetic responses. Where possible electric fence lines were turned off to avoid interference effects with the electromagnetic response.

Surveys were carried out in a variety of locations throughout the valley (Figure 3.14) to evaluate the merits of using TEM methods for identifying and mapping the aquifers and to determine thickness of the alluvial deposits. The majority of surveys were carried out adjacent to groundwater wells for which stratigraphic logs were available for correlation with the TEM data. The majority of the TEM surveys were conducted using both an 80 x 80 metre loop and a 40 X 40 metre loop. For localities where an 80 x 80 metre loop could not be fitted, a 60 x 60 or 40 x 40 metre loop was used. In addition, a 120 x 120 metre TEM survey was conducted by the 1999 Fourth Year Geophysics class to determine the maximum depth of penetration. The set-up parameters used for the TEM surveys are presented in Table 3.3.

A total of 28 TEM soundings were completed at 8 localities throughout the basin (Figure 3.14), and survey details are included in Table 3.4.

***Table 3.3 – TEM Set-up Parameters***

| Parameter | Setting | Description |
|---|---|---|
| Transmitter loop size | 40 x 40 metre<br>60 x 60 metre<br>80 x 80 metre<br>120 x 120 metre | |
| Transmitter loop turn-off time | 4.5μs/ 3.5μs | Time taken to shut off the current in the transmitter loop |
| Transmitter current | 2 Amps | Amount of current passed through the transmitter loop |
| Receiver coil area | $31.4m^2$ | |
| Integration time | 30 seconds | |
| Repetition rate | 237.5 / 62.5 / 25 / 6.25 Hz | |
| Gain | 1 / 3 / 5 / 7 respectively for the repetition rates above | Amplifies the signal |

### *3.3.2.3 TEM Results, Interpretation and Conclusions*

Figure 3.15 presents a schematic diagram of the nature of the survey targets, and the expected resistivities of the subsurface geological formations. Depth of penetration is expected to be at least 100 metres, and the targets are discrete water-bearing units incorporated within the Canterbury and Teviotdale Gravels, which overlie the Kowai Gravels.

Canterbury and Teviotdale Gravels are composed of clay and siltbound alluvium with expected resistivities of 50 to 500 ohm-m. The resistivity values shown in Figure 3.15 are quoted from various TEM surveys completed in Canterbury (Fields, 1999; Nobes, 1999; M. Armstrong, pers.comm., 2000). The wide range of resistivity values for the Canterbury and Teviotdale Gravels found in different localities throughout Canterbury is due to the degree of weathering, the proportion of fine sediments (i.e. clays and silts), and the degree of reworking and sorting of the gravels. The degree of sorting affects the permeability and porosity of the gravels, which influences the observed resistivity

*Figure 3.14 - TEM Sounding Locations*
*Number indicates sounding number for each survey location. Refer to Appendix C-5 for corresponding equivalence models.*

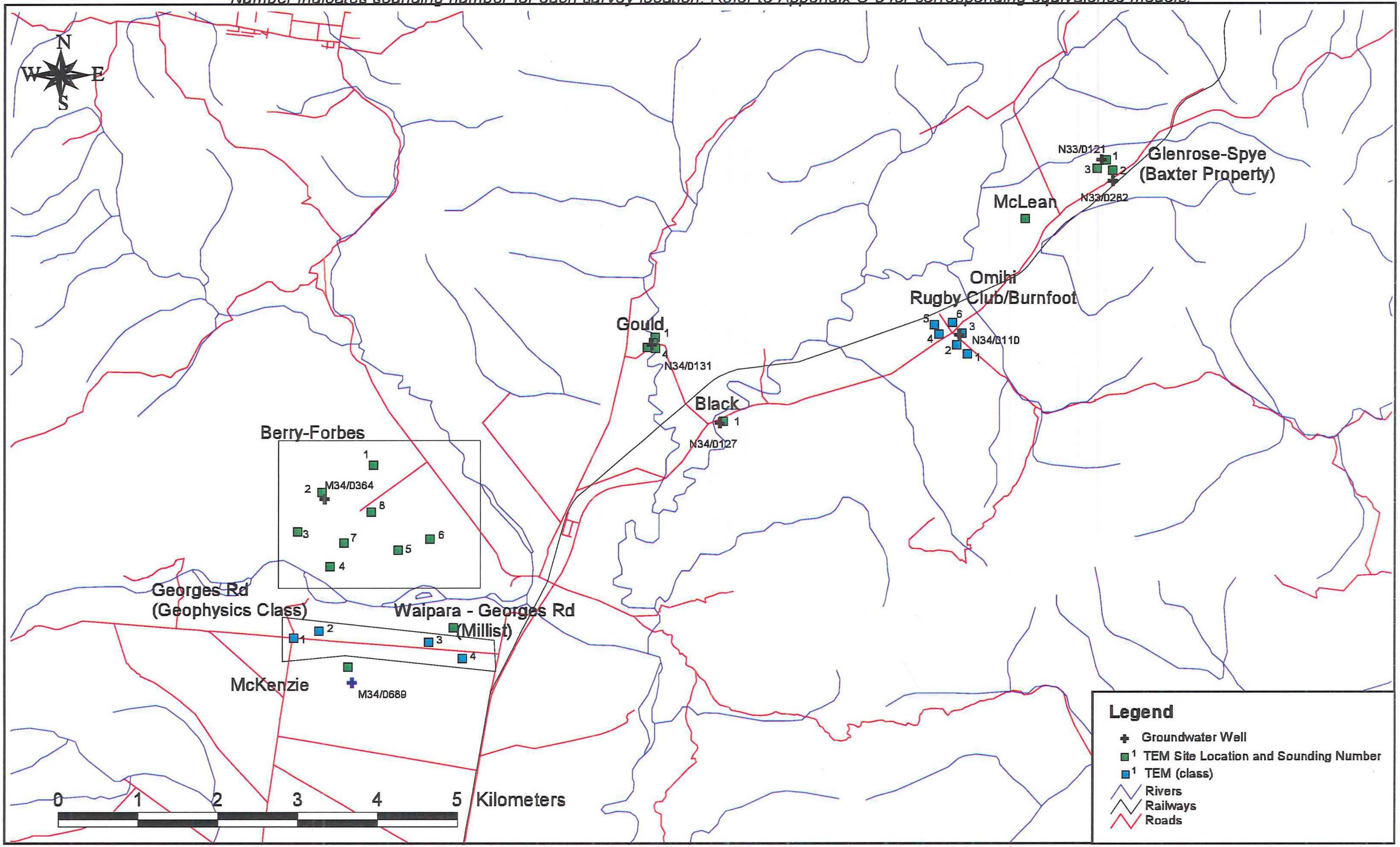
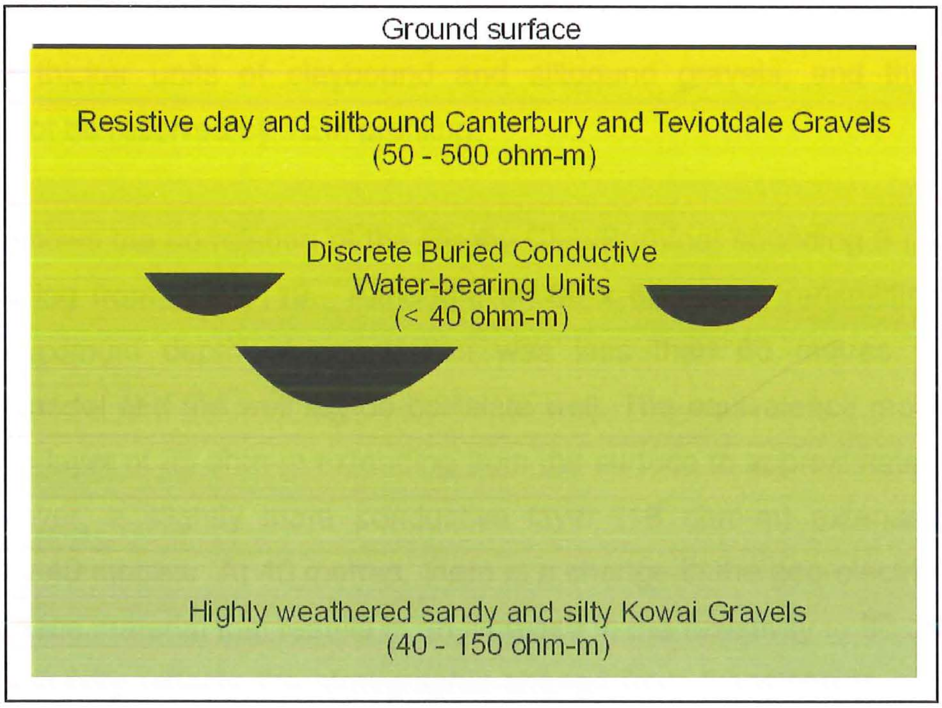


***Table 3.4 - TEM Survey Location Details***

| Map Reference | Locality | Well Number Correlation | Number of Soundings | TEM Transmitter Loop Size(s) |
|---|---|---|---|---|
| A | Glenrose, Omihi (Baxter Property) | N33/0121<br>N33/0268 | 3 | 80 x 80<br>40 x 40 |
| B | Omihi Stud, Omihi (McLean Property) | none | 1 | 80 x 80 |
| C | Glenmark Rugby Club/ Burnfoot, Omihi* | N34/0110<br>N34/0143<br>N34/0142 | 6 | 80 x 80 |
| D | Black Property, Omihi | N34/0127 | 2 | 40 x 40<br>60 x 60 |
| E | Glenmark (Gould Property) | N34/0131 | 2 | 40 x 40<br>60 x 60 |
| F | Waipara Downs, Waipara (Berry Property) | M34/0364 | 2 | 80 x 80 |
| G | Forbes Property, Waipara | M34/0364 | 6 | 80 x 80 |
| H | Georges Road<br>Millist Property<br>Mckenzie Property | M34/0726<br>M34/0689<br>M34/0765 | 6 | 80 x 80<br>120 x 120 |

(McNeil, 1990). The Kowai Gravels have an expected resistivity of 40 – 150 ohm-m (Nobes, 1999; M. Armstrong, pers.comm., 2000).

***Figure 3.15 – Schematic Diagram of Subsurface Geology and the Nature of the Targets for TEM Surveys. Expected Resistivities are shown in parentheses.***




TEM equivalence models are included in Appendix C-5. Overall, TEM data were of good quality, however, the depth of penetration for soundings of identical loop sizes were variable for the different survey locations, and the observed apparent resistivities were much lower than the expected values shown in Figure 3.15. The maximum depth of penetration achieved without loss of resolution was approximately 150 metres, and was achieved by use of the 120 x 120 metre transmitting loop on Georges Road. The majority of the 80 x 80 metre soundings penetrated to a depth of 100 metres, and therefore, the subsurface medium at depths greater than 100 metres could not be resolved.

### 3.3.2.3.1 Aquifer Identification and Delineation

Figure 3.16 is a typical example of the poor correlation between the well logs and the TEM equivalence models. The TEM data for the Waipara Downs sounding 2 (Figure

3.14) shows three distinct geo-electric boundaries, however, they do not correlate with the logged stratigraphic boundaries. Most importantly, the figure shows how the 2 metre thick conductive water-bearing unit is masked by the surrounding conductive clay-rich lithologies. Examination of the well logs included in Appendix B-1 show that majority of the aquifers in the Waipara basin are relatively thin, and often surrounded by considerably thicker units of claybound and siltbound gravels, and therefore, the aquifers cannot be resolved by TEM profiling.

Figure 3.17 shows the correlation of the Rugby Club/Burnfoot sounding 3 (Figure 3.14) with the well log from N34/0110. Although, an 80 x 80 metre transmitting loop was used, the maximum depth of penetration was less than 60 metres. The TEM equivalence model and the well log do correlate well. The equivalence model shows a more resistive layer of 25 ohm-m extending from the surface to approximately 7 metres. Below this layer, a slightly more conductive layer (18 ohm-m) extends from 7 to approximately 40 metres. At 40 metres, there is a change in the geo-electric properties of the subsurface material that results in an increase in the resistivity to 80 ohm-m. The change in resistivity reflects the stratigraphic change from limestone to water-bearing gravels. Because the overlying limestone is conductive, it absorbs the TEM signal, and therefore limits the depth of penetration. Typically, water-bearing units should represent the lowest resistivity, however, in this example, the lowest resistivity is exhibited by the limestone and not the more resistive water-bearing gravels. It is concluded that the change in the resistivity a more a reflection of the contrasting physical properties of the strata than the presence of groundwater.

Four TEM soundings with a 120 x 120 metre loop were completed along Georges Road in Waipara (H). Figure 3.18 is a geo-electric cross-section drafted by the students of the 1999 Fourth Year geophysics class. A geo-electric boundary is identified at approximately 20 metres, which correlates to a 20 – 30 metre aquifer as shown in the well logs for M34/0686 – M34/0692. Additional geo-electric boundaries are identified by a decrease in the apparent resistivity at 60 – 100 metres, and at 180 – 220 metres, and may correlate to the Teviotdale – Kowai boundary. The increase in conductivity with

***Figure 3.16 – Correlation of Waipara Downs TEM Equivalence Model with M34/0364 Well Log***

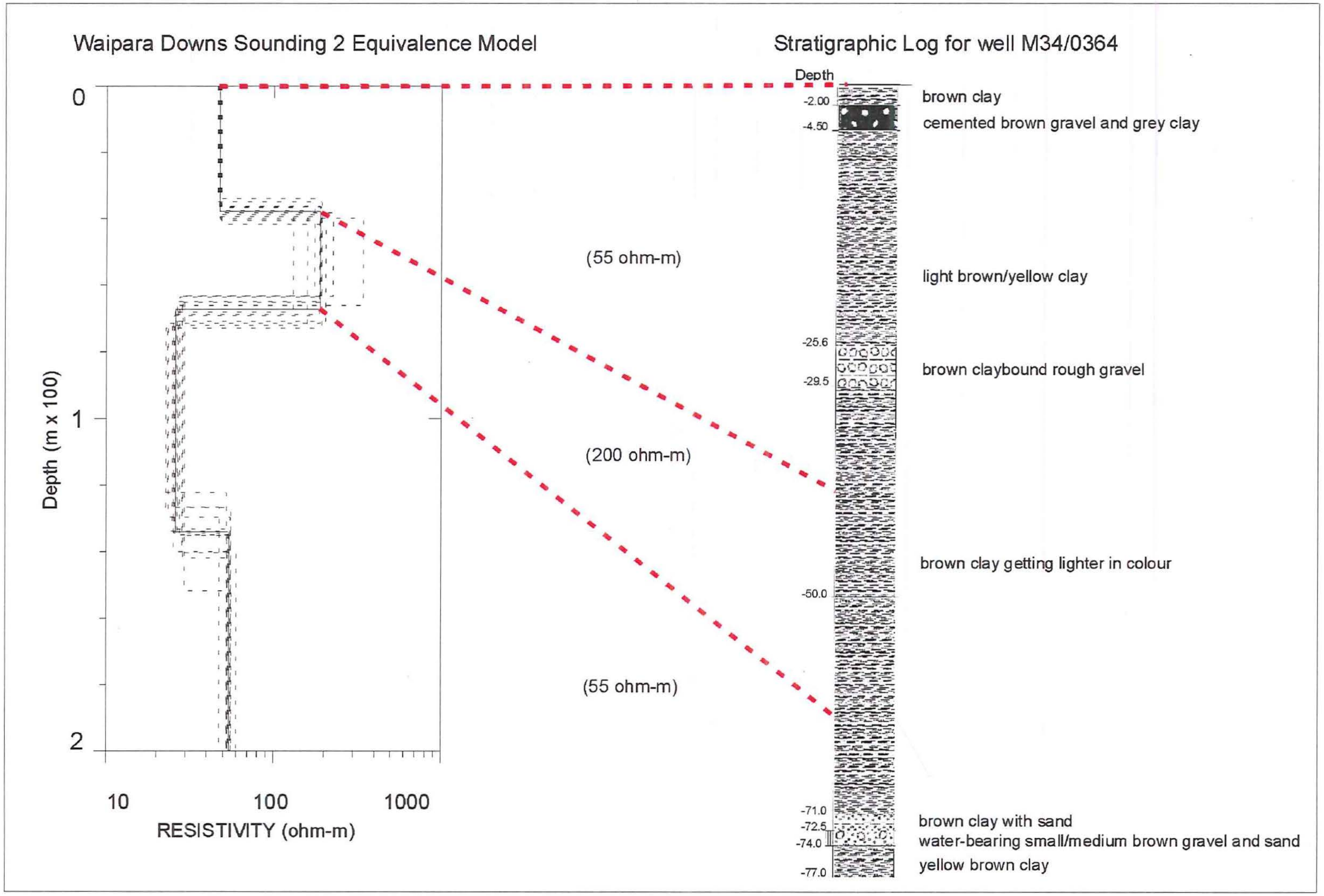
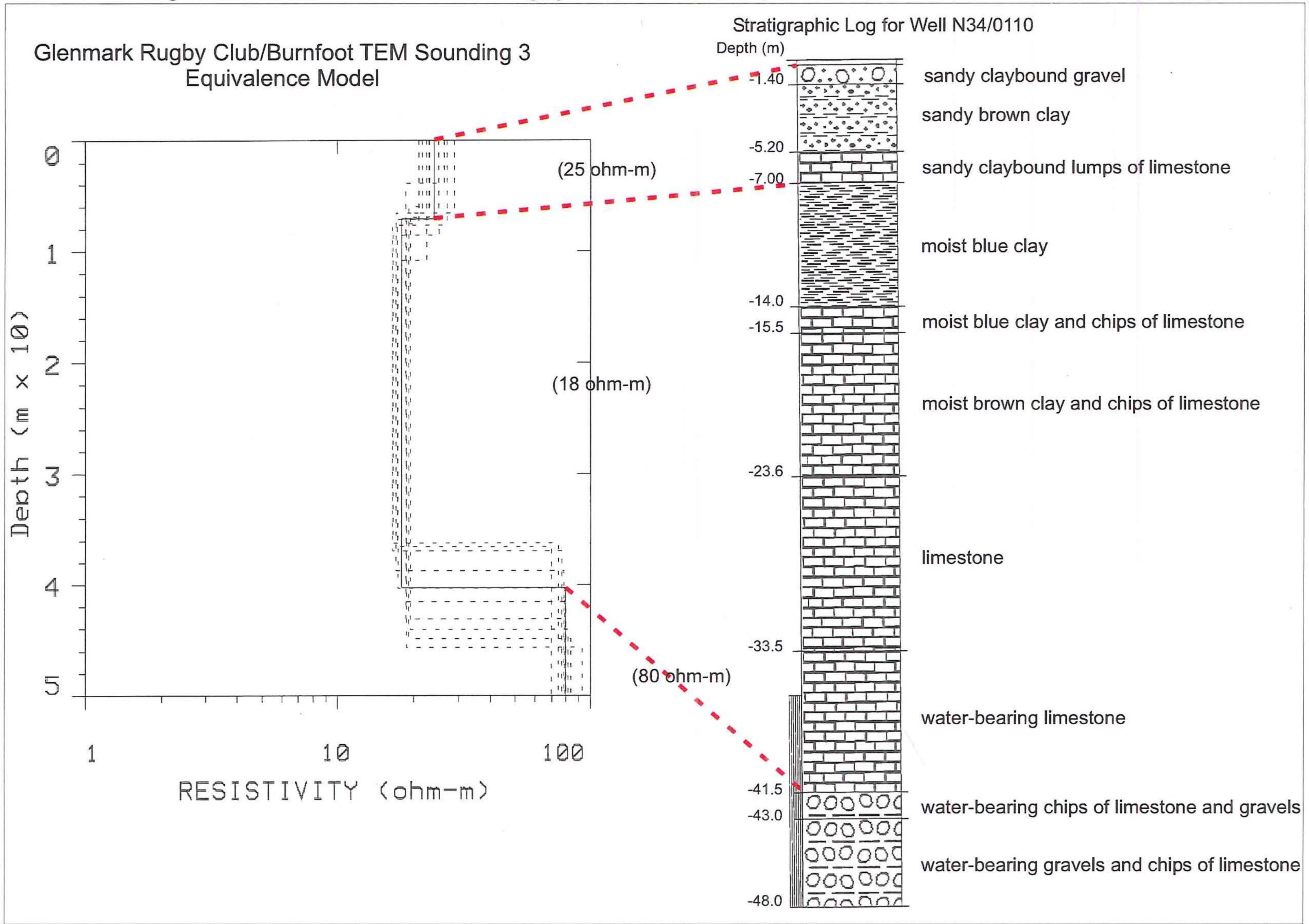


***Figure 3.17 - Correlation of the Rugby/Burnfoot TEM Equivalence Model with N34/0110 Well Log***



depth suggests that the observed apparent resistivities reflect changes in the geo-electric properties of the gravel formations, rather than with the occurrence of aquifers. The TEM may be capable of identifying the shallow aquifer, but it is not capable of delineating its vertical extent simply because the aquifers are relatively thin, and become masked by the surrounding subsurface material.

Figure 3.19 provides an example of the local heterogeneity of the geo-electrical properties of the subsurface geology. The data presented is from the Glenrose Survey in which two soundings were completed approximately 250 metres apart. Both models are well constrained as shown by the minimal spread of the equivalence lines. However, correlation of the geo-electrical boundaries is not possible because of the local variation in the cover deposits.

3.3.2.3.2 Regional Variations Identified from TEM Results

Comparison of TEM results from surveys of similar loop size show that the depth of penetration in the northern part of the valley in Omihi and Glenmark is restricted to less than 60 metres. Conversely, TEM soundings completed at Waipara Downs, the Forbes property, and along Georges Road in the central part of the basin had greater depths of penetration. Because the depth of penetration of the TEM signal is greatly affected by the geophysical properties of the underlying geology, the differences in depth of penetration for the two areas is best explained by differences in the subsurface geology (i.e. gravel lithology, clay and silt content), and possibly changes in the ionic character and thus, conductivity of the groundwater. In addition, the observed apparent resistivities for surveys conducted in Omihi are much lower than expected, and lower than the observed apparent resistivities for the surveys conducted in the central part of the basin. Both the restricted depth of penetration and the low observed resistivities in the southern part of the basin are most likely attributed to the conductive clays and silts. Lithologic samples collected from drilled wells show that the Omihi gravels have higher proportions of limestone-derived clasts, calcareous silts and clays, and iron stained gravels. Thereofre, it is suggested that the low resistivity measured by the TEM methods reflects both the geo-electrical properties of the subsurface material, may also reflect the ionic character of the groundwater (Chapter 5). Although, limestone is

*Figure 3.18 – Geo-electric Cross-section of Georges Road TEM Soundings (Beeching and Ryan, 1999).*

**Figure 3.18 Geo-electric Cross-section of Georges Road TEM Soundings (Beeching and Ryan, 1999).**

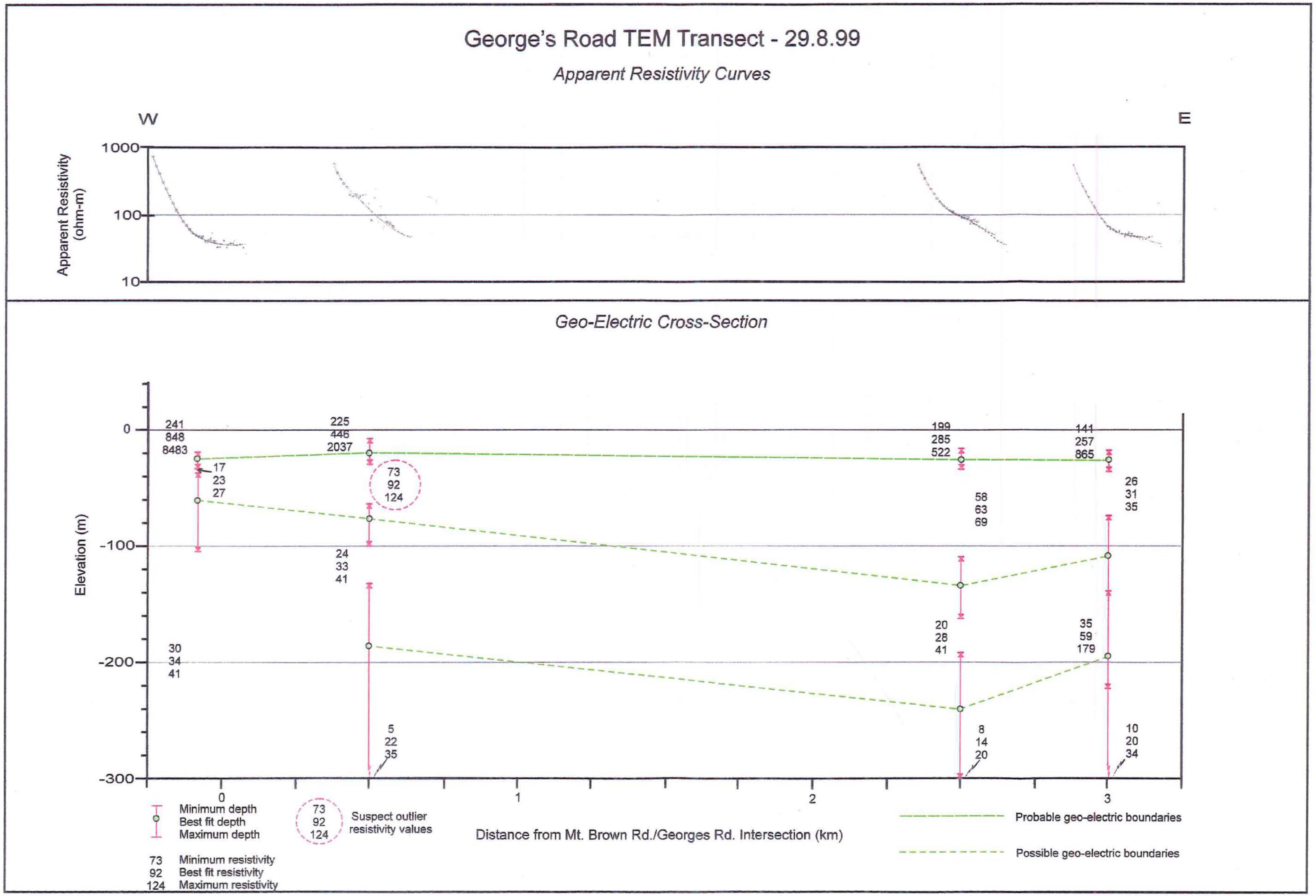
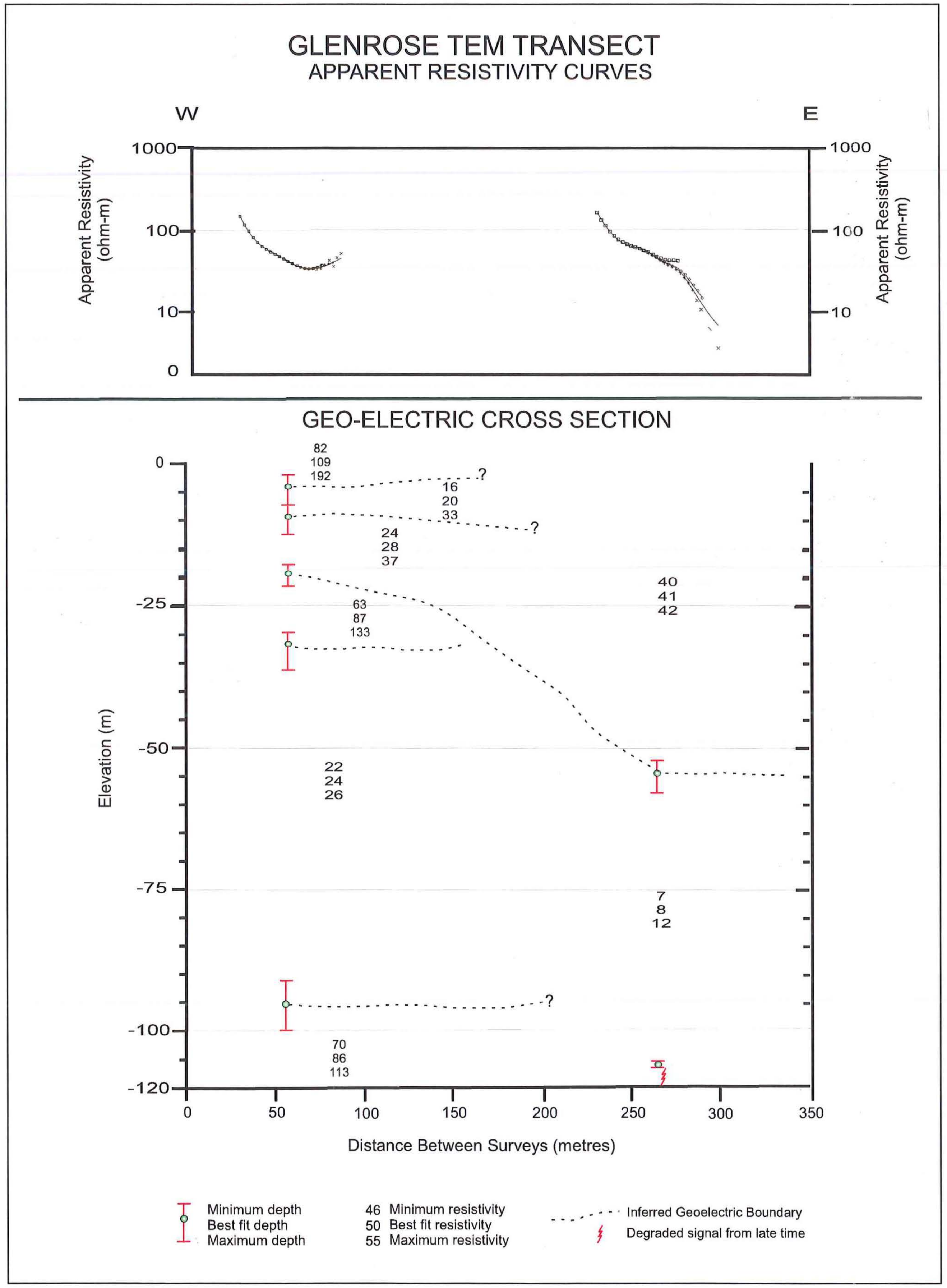
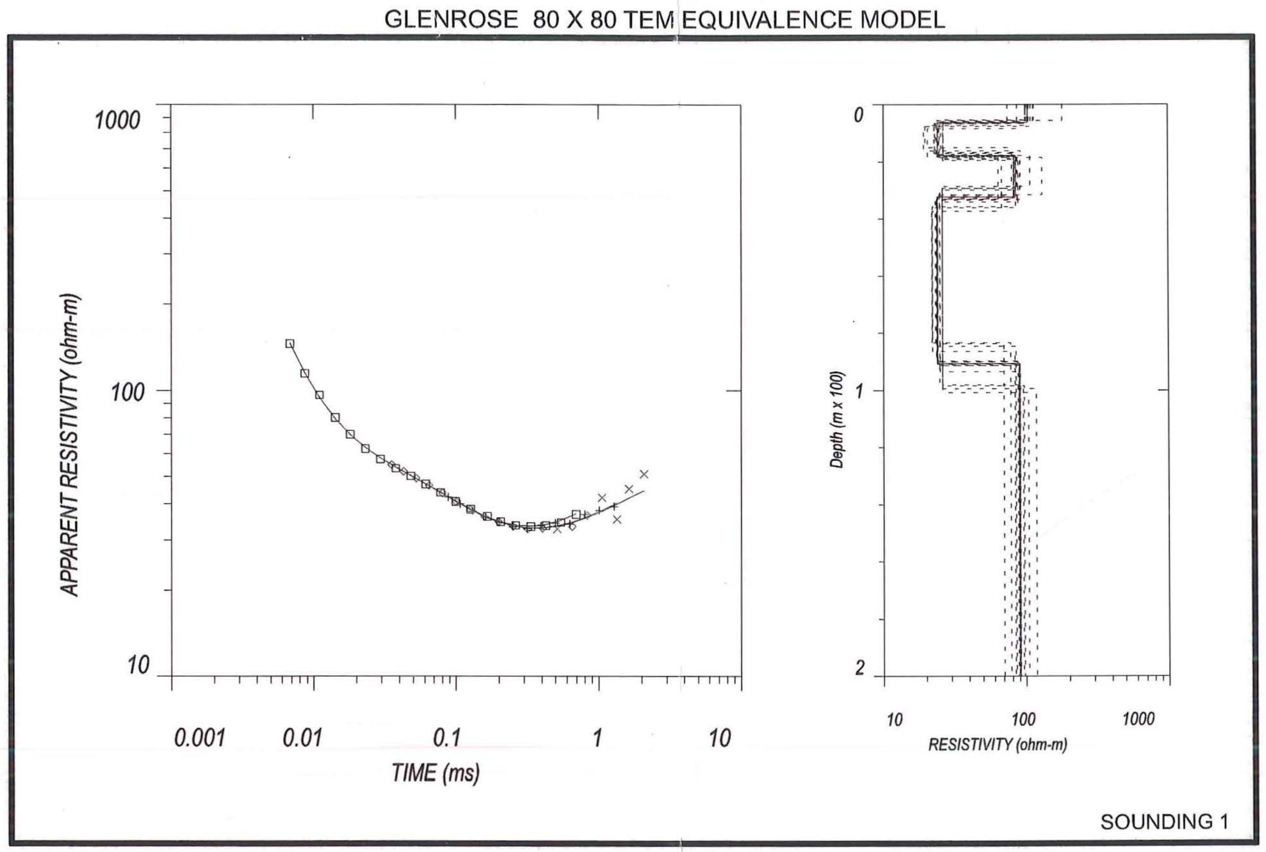
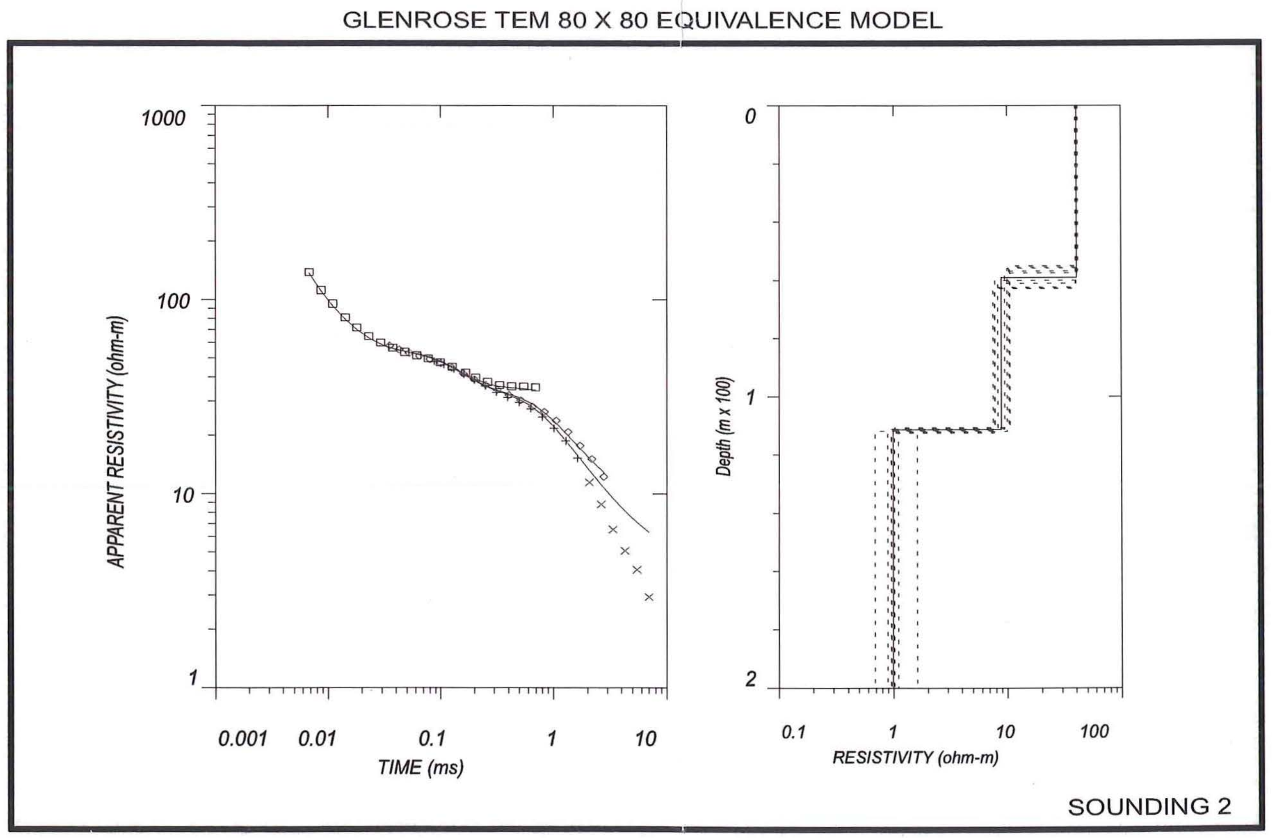


Figure 3.19 - Geo-electric Cross-section with Equivalence Models



generally a resistive material, however, when it interacts with groundwater, it can considerably increase the ionic content of the groundwater, especially if the groundwater has a long residence time in the host rock. Because the limestone and the calcareous silts and clays are conductive, the TEM signal is attracted to the conductive medium, and inhibits the depth of penetration. In the central part of the basin, the gravels are composed predominantly of greywacke, which is more resistive than limestone, thereby enabling better penetration depth of the TEM signal.

## *3.4 Chapter Summary*

### 3.4.1 Gravity

Gravity modelling and interpretation of the Glenrose-Spye survey suggests that the thickness of the cover deposits range from 300 metres at the eastern end of the survey line to 400 metres to the west. The minimum thickness of the cover deposits is approximately 150 metres. Interpretation of modelled data suggests the presence of an anticline towards the western end of the survey, possibly formed by concealed thrust faults at depth.

Modelled data from the Georges Road gravity survey suggests that the thickness of the cover deposits range from 900 metres to 250-300 metres. The resulting model suggests that the basement topography is disrupted by faulting at depth, and is not as uniform. Gravity anomalies are attributed to the presence of eastward verging reverse/thrust faults at the western end of the survey line, and westward verging reverse/thrust faults at the eastern end of the survey line.

### 3.4.2 Time-Domain Electromagnetics (TEM)

Results from the TEM surveys conducted throughout the region show that TEM methods cannot adequately resolve the aquifers. In addition, the depth of penetration is limited in the northern part of the basin as a result of the influence of limestone-groundwater interaction, and calcareous deposits and clay impurities, which increase the ionic concentrations and conductivity, thereby trapping the TEM signal. The TEM methods are capable of resolving geo-electric boundaries, however, they do not correlate well with the stratigraphic boundaries as indicated by well logs therefore making the interpretation of TEM data difficult. TEM methods were successful in identifying regional variations in the geo-electrical properties of the subsurface. The Omihi region is more conductive and therefore depth of penetration in places is limited. The subsurface alluvium in the Waipara region tends to be more resistive, allowing better depths of penetration. However, the maximum depth of penetration without losing resolution is approximately 200 metres. Overall, TEM methods are not recommended for locating and mapping aquifers in the Waipara basin.

# CHAPTER FOUR
# HYDROGEOLOGY OF THE WAIPARA BASIN

## 4.1 Introduction

The hydrogeological resources of the Waipara basin are one of the most important resource in the valley, and the future development of the area is dependent upon the sustainability of the groundwater water resource. This chapter describes and evaluates the water resources of the Waipara Valley. Groundwater investigations were carried out in order to describe and define the hydrogeological system(s), both qualitatively and quantitatively.

Groundwater resources of the Waipara Basin include both subsurface aquifers penetrated by groundwater wells, and groundwater springs. Aquifers are described and defined in terms of spatial and vertical distribution, lithology, yield, aquifer parameters (i.e. transmissivity, storativity, hydraulic conductivity), and seasonal and local water table fluctuations associated with groundwater recharge.

Springs occur in various localities throughout the basin, providing an important resource for many landowners in the area. Prior to this study, only three springs in the study area were recorded in the ECAN springs database. An investigation of springs was conducted to assess the surface-groundwater interaction, and identify sources of recharge and discharge into the basin. In addition, surface water investigations included flow gauging of the Waipara River, and evaluation of existing gauging data for Weka Creek, Omihi Stream and Home Creek to identify stream-groundwater interaction for the northern part of the basin.

## 4.2 Groundwater Resources: Aquifer Description and Delineation

There are approximately 280 wells located within the study area of which only 60% are actively used at present. Aquifers occur at a wide variety of depths on a local and regional scale, attesting to the geologic variability. Stratigraphic logs indicate that aquifer conditions range from semi-confined to confined aquifers. Truly unconfined aquifers are rare, and unconfined conditions are most likely to be found adjacent to modern day river courses. Unconfined conditions may also exist in shallow aquifers in other parts of the region, but the lack of bore log information, and pump test data makes this difficult to assess.

There are three flowing artesian wells in the region (N34/0139, N34/0131, M34/0726) and two subartesian wells (N34/0106 and N34/0107). All other wells located within the basin are non-flowing artesian. Figure 4.1a (pocket) shows locations of selected wells and the depth distribution of wells throughout the basin Waipara basin. Transects for which cross-sections have been constructed are shown.

The aquifers evaluated in this study occur in the Canterbury (waipara and omihi gravels), Teviotdale, and Kowai Formations, which includes the lower Kowai/Greta Beds. Aquifers are located at a variety of depths throughout the region as shown in by constructed hydrogeological cross-section in Figures 4.2a, 4.2b and 4.2c. Wells penetrate aquifers located between 4 – 12 metres below ground level (mbgl), 20 – 35 metres, 50 – 65 metres, 75 – 86 metres, and between 90 – 120 (mbgl). The deepest well in the basin is 170 meters (N33/0282) and is located at the northern limits of the field area by Spye (Figure 4.1). All constructed cross-sections and lithology codes for the hydrogeologic cross-sections are included in Appendix D-1.

Water-bearing units are typically composed of sandy gravels, claywashed gravels, and silty gravels derived from the Torlesse and Tertiary sequences. Semi-confining and confining layers consist of yellow-brown silty claybound gravels, yellow-brown clays, and blue silts and clays. Drill cuttings collected from 10 wells drilled during the course of this study have provided some stratigraphic constraints and information for characterising the aquifers lithologies as a function of depth and geographic location. Sediment analyses (Appendix D-2) conducted on a total of 11 samples collected from different wells indicate that shallower aquifers (4 – 35 mbgl) and sediments have a higher content of clay (loess) and silty gravels, and silt gravels dominate the deeper aquifers.

**Figure 4.2a - Hydrogeological Cross-section A - A' (Spye to Waipara). Well numbers are indicated above the well, well depth(metres) is indicated at the bottom. Well screens are are shown as an indentation in the well casing. Definitions of lithology codes are presented in Appendix D-1.**

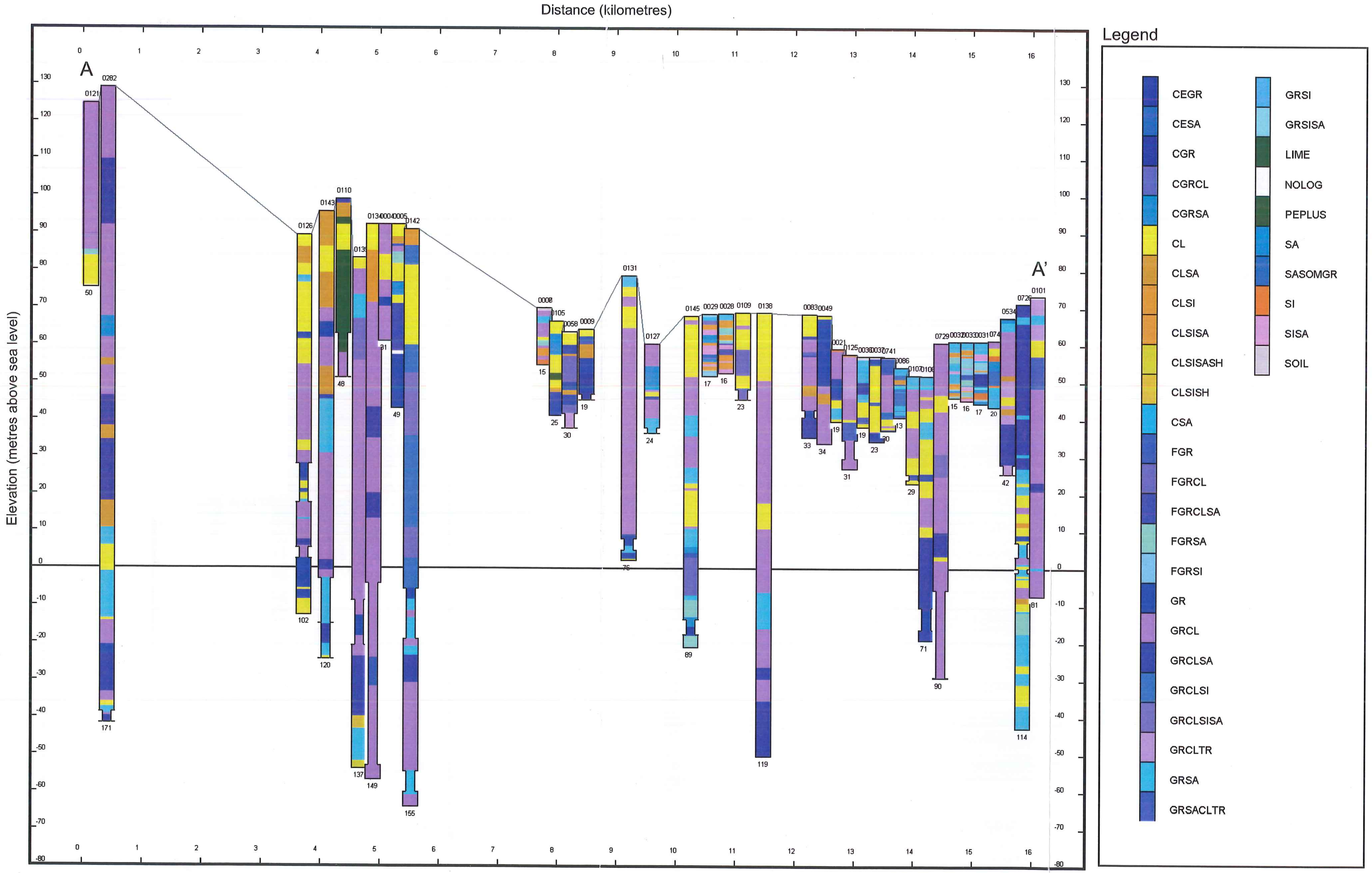


***Figure 4.2b - Hydrogeological Cross-section B-B' (Waipara to Amberley). Well numbers are indicated above the well, well depth (metres) is indicated at the bottom. Well screens are are shown as an indentation in the well casing. Definitions of lithology codes are presented in Appendix D-1. Refer to legend in previous cross-section.***

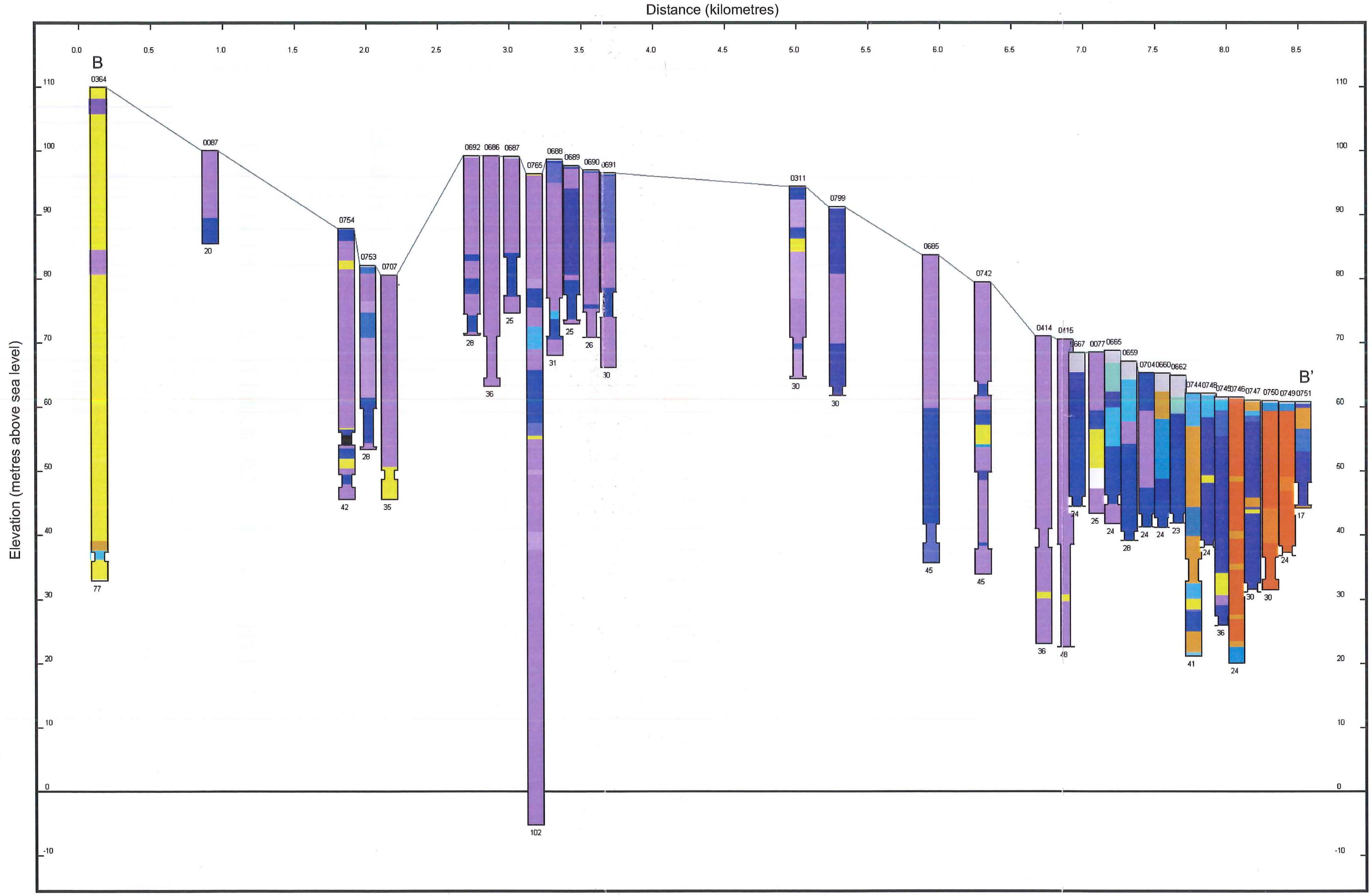
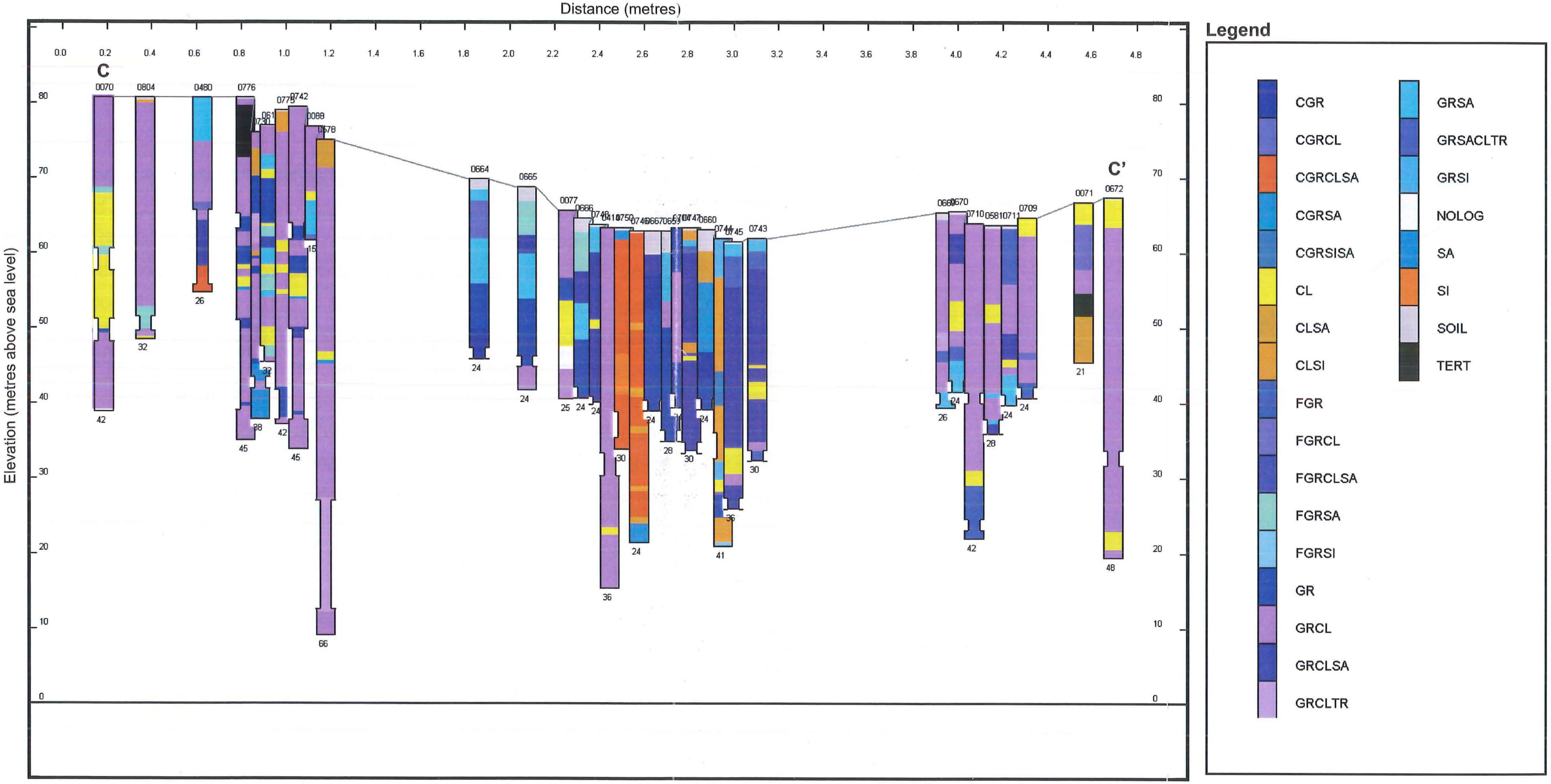


***Figure 4.2c - Hydrogeological Cross-section C-C' (west to east). Well numbers are indicated above the well, well depth (metres) is indicated at the bottom. Well screens are are shown as an indentation in the well casing. Definitions of lithology codes are presented in Appendix D-1.***



### 4.2.1 Regional Delineation

It has been shown in Chapter Two that the depositional history of the Omihi Valley differed from that of the central and south Waipara regions. Geophysical data from TEM methods show that the geo-electrical properties of the subsurface medium in Omihi is more conductive and differs from the geo-electrical properties exhibited by the southern part of the basin demonstrating that there is a difference in the subsurface alluvial deposits.

Analysis of well logs (Appendix B-1) and samples collected from wells show that the alluvium deposited in Omihi tend to have higher proportions of Tertiary derived gravels than the alluvium deposited in the Waipara – Amberley region. Alluvial deposits in the southern part of the basin tend to be dominated by greywacke and argillite, which provides clues about the geologic source of the deposits. Samples collected from a suite of wells in Omihi (N34/0134, N34/0142 and N34/0145) show a marked increase in Tertiary derived gravels between 40 and 70 mbgl, and gradually decreases in abundance with increasing depth. The stratigraphic units dominated by limestone clasts may signify periods of increased tectonic activity resulting in erosion of the uplifted and exposed Tertiary sequences. Stratigraphic logs with photographs of lithologic units for selected wells for which drill cuttings were collected are included in the back pocket and labelled according to well number.

### 4.2.2 Hydrogeologic Delineation

Table 4.1 outlines the delineation of aquifers in terms of their distribution within geologic formations, yield, thickness and lithology. However, aquifer yields and thickness are extremely variable and inconsistent.

Aquifers occurring within Canterbury (waipara and omihi) and Teviotdale Gravels exhibit similar physical properties (lithology, yield, and thickness), and cannot be distinguished from one another without the identification of the Aokautere Ash (see Chapter 2), and/or loess deposits. In addition, the poorly constrained depositional history of aggradation and degradation events, and associated tectonic activity complicates the spatial distribution of the formations and associated aquifers, as demonstrated in Chapter Two.

**Table 4.1 – Aquifer Identification and Delineation Based on Lithology, Depth of occurrence, and Reported yields.**

| *Formation Aquifers* | *Depth Range (mbgl)* | *Yield (l/s)* | *Lithologic Description* Showing Regional Variations* | |
|---|---|---|---|---|
| | | | Waipara | Omihi |
| Recent Deposits | flood plains adjacent to modern day stream courses | 2 – 22 | Large boulders and gravels composed predominantly of greywacke; some Tertiary Limestones and Sandstone with silt and clay | Large boulders and gravels composed predominantly of Tertiary derived clasts with calcareous silts and clay |
| Undifferentiated Canterbury Gravel Aquifers (CTA) | 2 – 50 | .2 – 3.0 | Greywacke gravels claywashed and claybound brown-grey silt and clay matrix; | Greywacke claywashed and claybound gravels with brown-silt and clay; |
| Undifferentiated Teviotdale Gravel Aquifers (CTA) | | | Weathered greywacke gravels increase in Tertiary derived clasts with depth; yellow-brown silty clay; | Weathered clasts predominantly derived from Tertiary Formations with yellow-brown silty clay; |
| Undifferentiated Kowai Gravel Aquifers, including Lower Kowai/Greta Beds* (KGA) | > 50 | 2.0 – 20 | Large rounded, weathered gravels, composed of predominantly of Torlesse derived clasts, often with iron staining, and higher proportion of sand than silt; Proportion of limestone derived gravels decreases with depth; occurrence of shells indicative of transition from Kowai to Lower Kowai (Greta Beds); | |

* Aquifer lithologies will vary as a result of localised influences in the depositional history and catchment source

Aquifers occurring in formations believed to representative of the Canterbury and Teviotdale Gravels have been delineated as undifferentiated Canterbury -Teviotdale Gravel Aquifers (CTA). A review of the estimated late Pliocene and Quaternary formation thicknesses from previous geologic studies, and collection of drill cuttings, provided some constraint for distinguishing the aquifer systems(s) in terms of subsurface stratigraphy. Aquifers occurring at depths greater than 50 metres are assumed to be included in Kowai Gravel, and are termed undifferentiated Kowai Gravel Aquifers (KGA). The boundary between the aquifers occurring within the CTA and KGA is determined from the estimated stratigraphic thickness' (Wilson, 1963; 1983), examination of drill cuttings, and aquifer yields. The KGAs are composed of more rounded gravels, often exhibiting limonite staining, in a silty, sandy matrix. The CTAs contain higher proportions of silt and clay, and greywacke gravels. Figure 4.3 is photographs of selected drill cuttings illustrating the aquifer lithologies and semi-confined and confined units.

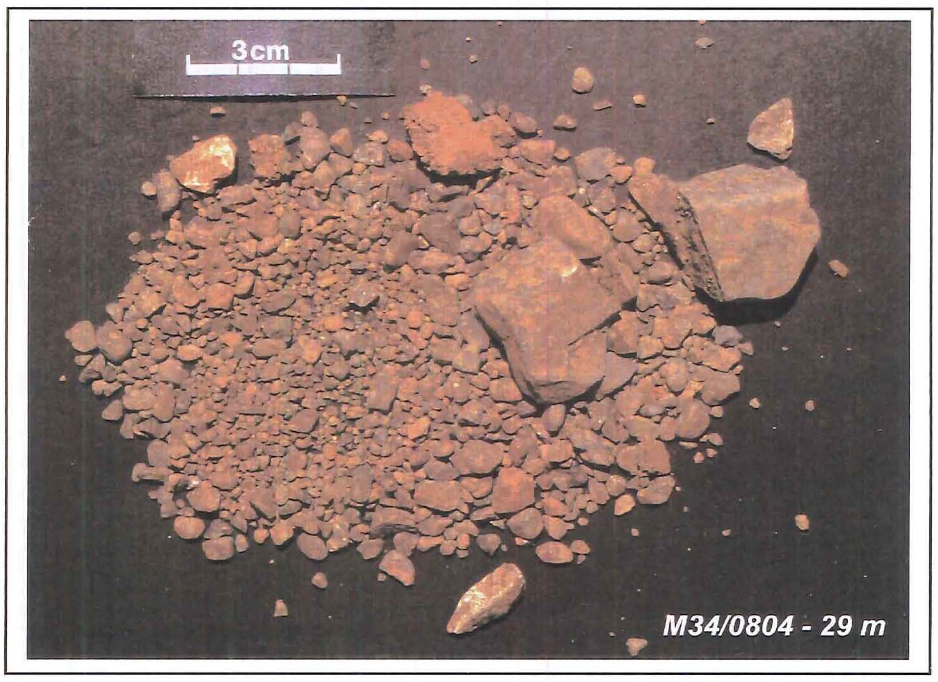
The depth of the formation boundaries and aquifer lithology will vary throughout the region as a result of local unconformities associated with local aggradation and degradation events, local differential uplift and deformation due to faulting and folding. The suggested boundary depths are not absolute determinations and require further collection, documentation and analysis of subsurface strata during drilling.

### 4.2.3 Aquifer Yield and Thickness

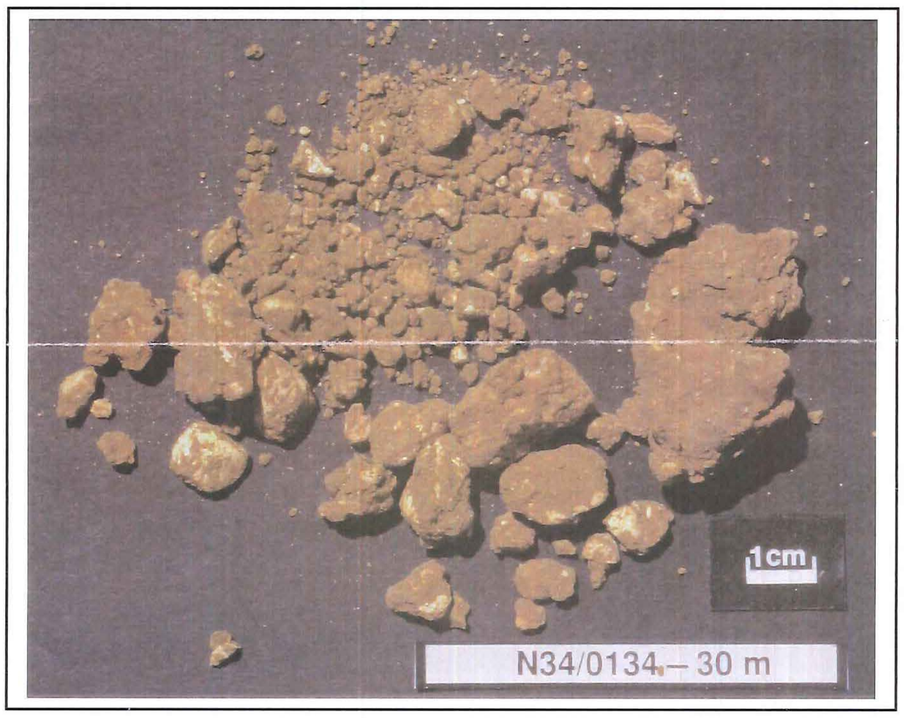
Safe yields for the alluvial aquifers occurring within the Waipara Basin range from 0.5 l/s to 20 l/s. They are lithologically heterogeneous and thicknesses vary over short distances. The average aquifer thickness is 5 metres. Because individual aquifers are low yielding, approximately 50% of the existing wells are screened over several water-bearing units in order to maximise the well yield. Well yields are variable throughout the region, and correlation between well yield as a function of geographic location (Figure 4.4) and correlations between well yield as a function of depth (Figure 4.5) are poor. Recent wells drilled in Omihi and Glenmark are the best yielding wells in the region (i.e. greater than 10 l/s), and all penetrate to depths greater than 70 metres, suggesting that the deeper aquifers are more permeable. Aquifers penetrated by these wells

***Figure 4.3 – Photographs of Drill Cutting Samples Showing Typical Water-Bearing Units and Characteristic Confined and Semi-confined Units***

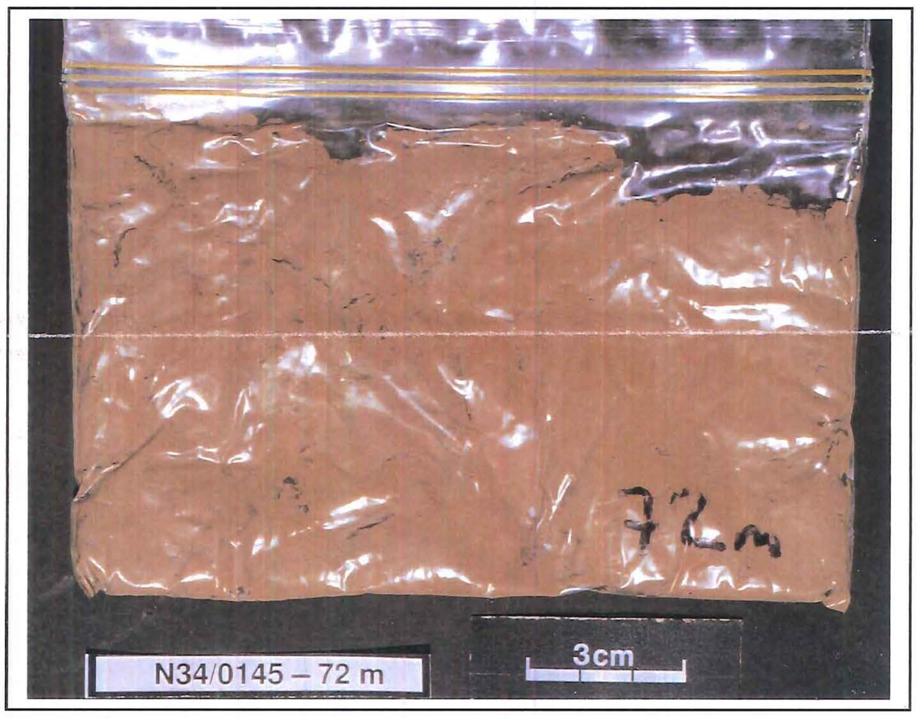

*a) sandy gravels (KGA)*



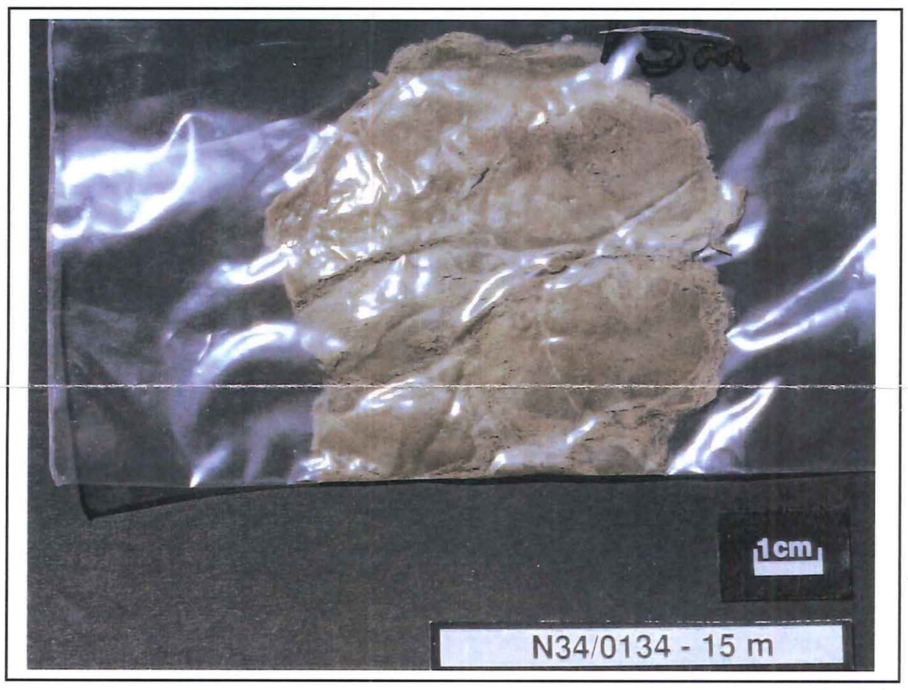

*b) claywashed gravels (CTA)*




*c) semi-confining layer: claybound gravels*




*d) confining layer: brown clay*




*e) semi-confining layer: grey-brown clay*


*f) semi-confining layer: silty clay and gravels*

***Figure 4.4 – Geographic Distribution of well Yields throughout the Waipara Basin***

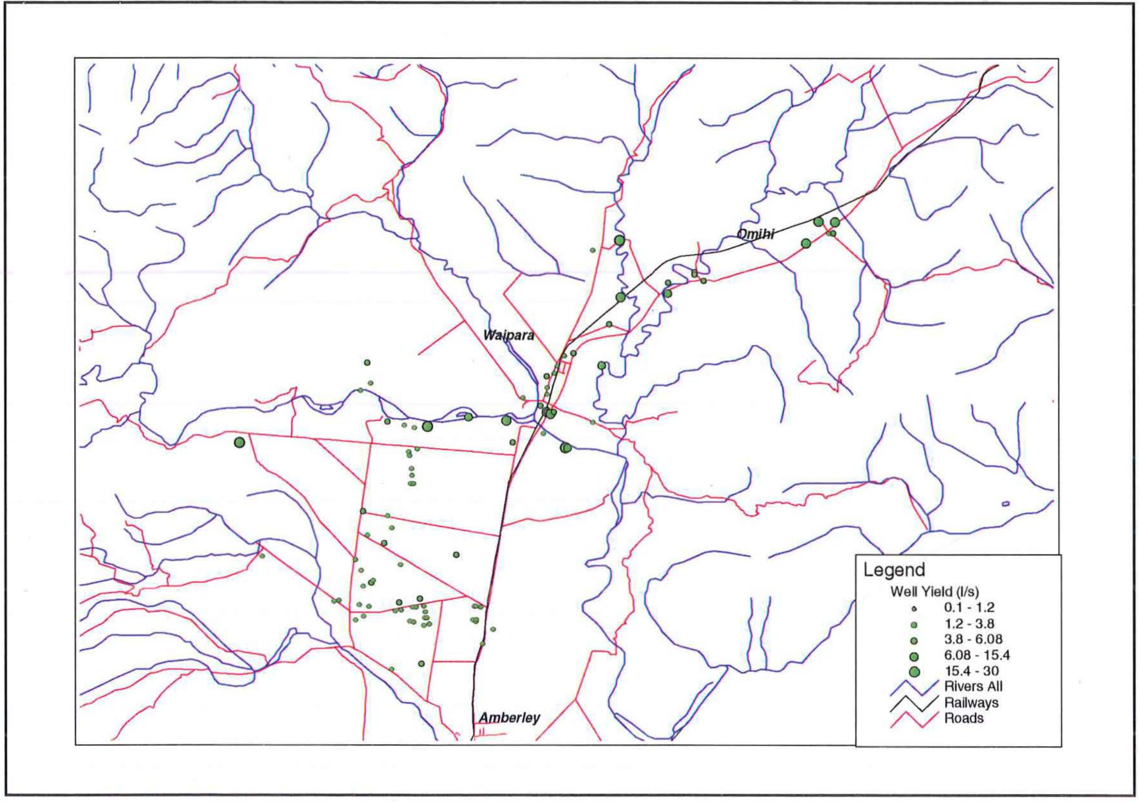
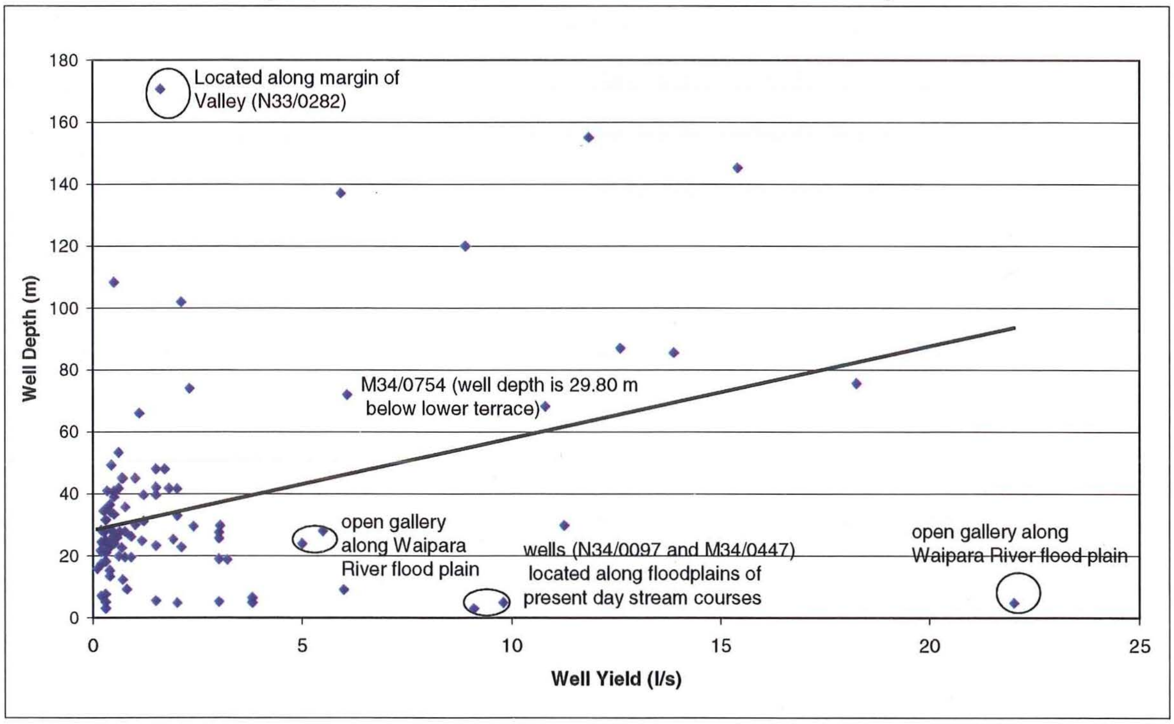



***Figure 4.5 - Well yield as a Function of Well Depth***



(N34/0131, N34/0139, N34/134, N34/0139, N34/0142 and N34/0143) have been identified as Kowai Gravel Aquifers (KGA). In addition, a well recently drilled to 160 metres on the south side of the Waipara River is estimated to yield a total of 20 l/s, further suggesting that the deeper aquifers are higher yielding. The well penetrated approximately 160 metres of clay and claybound gravels before reaching a potential aquifer, and the well screen is 40 metres long extending over several water-bearing units. Well N33/0282, located in the northern limits of the study area, is the deepest well in the region (170 metres), and yields only 2 l/s. The well is located along the margin of the valley, and the thick accumulation of clay and silts, suggests that this may have been the location of an ancestral flood plain. Several shallow wells (< 15 metres) have high yields, but these wells are large diameter wells located along the modern day floodplains of the Waipara River, Weka Creek and Omihi Stream.

### 4.2.4 Potentiometric Surface and Regional Groundwater Flow Direction

A potentiometric survey was carried out in August of 1999 for a total of 92 wells located throughout the basin. Groundwater well elevations were established by using differential GPS and a staff and level.

All Figure 4.6 shows the measured potentiometric surface elevations for all wells surveyed. Coloured symbols are used to delineate aquifers of similar depths. The variable measured potentiometric surface of the wells reflects the lateral discontinuity of the aquifers, and the fact that the wells are screened over multiple aquifers to increase the well yield.

Construction of a regional potentiometric surface proved to be difficult because most wells are screened over several aquifers and therefore, the resultant measured water level represents a cumulative pressure effect from each individual water-bearing unit. Regional flow directions (Figure 4.7) were determined by constructing potentiometric contours for wells located within a small areal extent that were believed to be hydraulically connected based on stratigraphic data and recorded water levels. Figure 4.7 shows constructed potentiometric contours. The potentiometric contours could not be extended to cover a larger area than shown due to insufficient data, and the lack of

*Figure 4.6 - Potentiometric Surface Data (August 1999)*

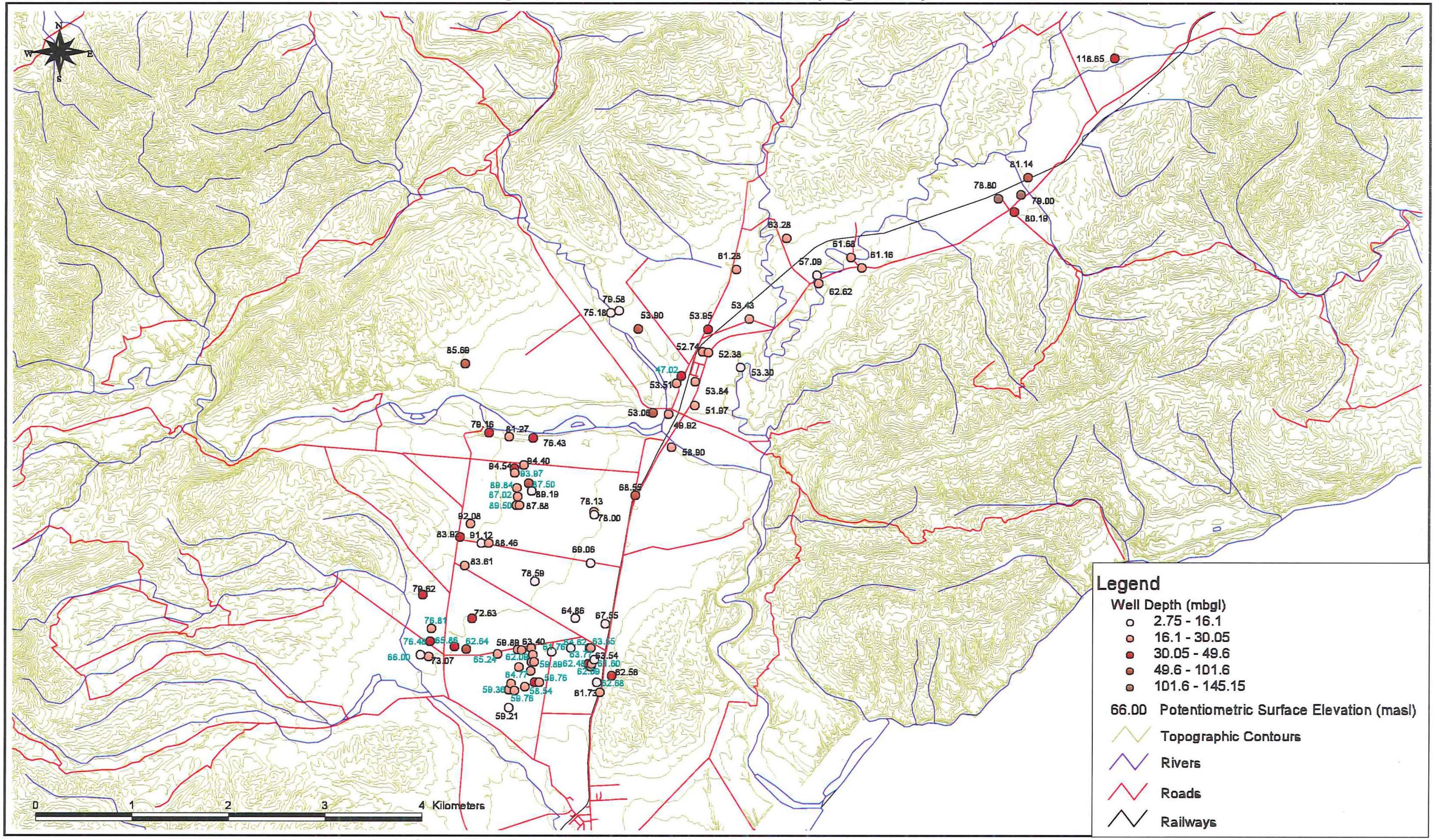
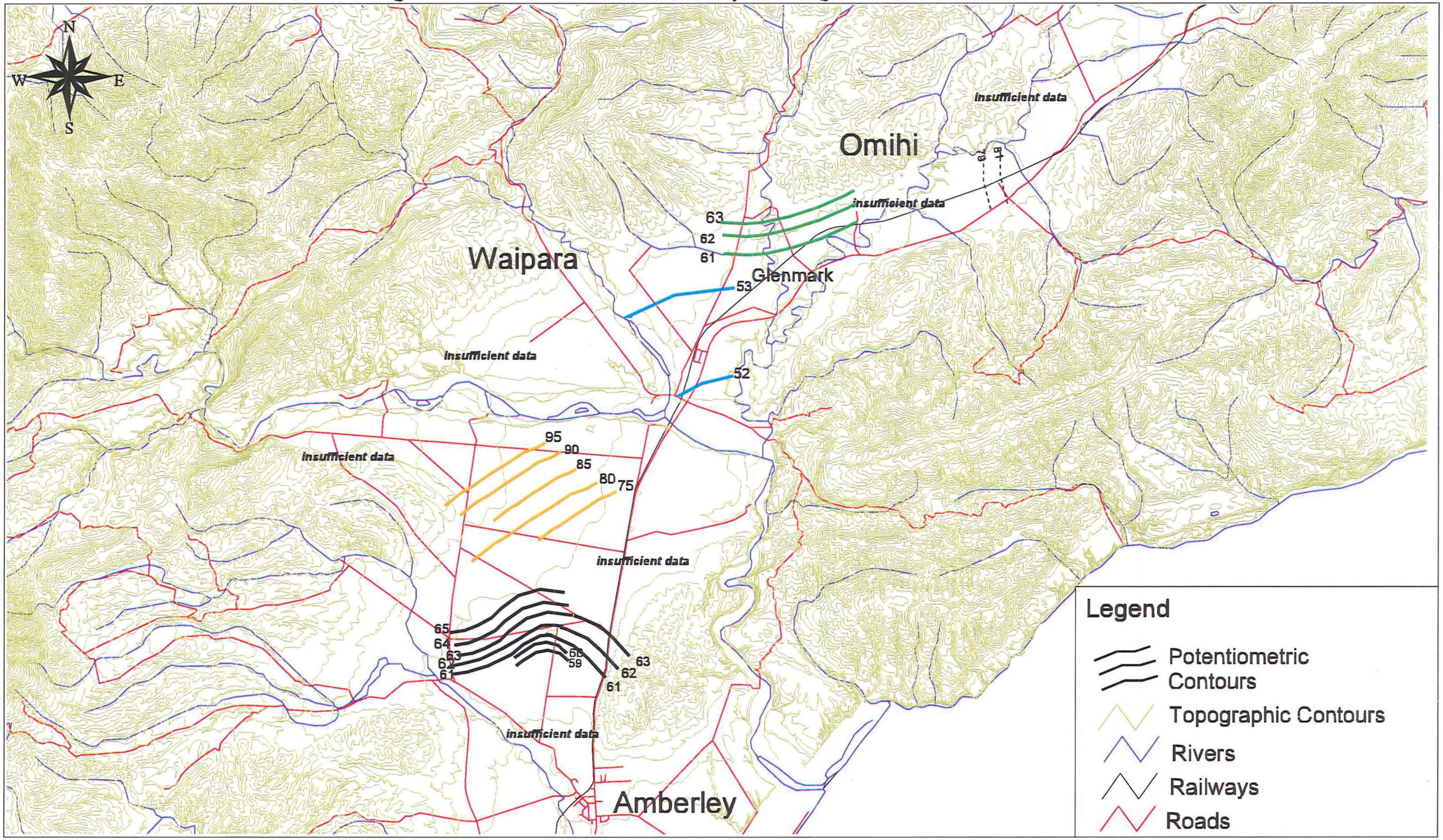


***Figure 4.7 - Potentiometric Surface Map Showing Groundwater Flow Directions***



bores penetrating the same aquifer.

Based on the collected data it can be shown that the hydraulic gradient is small and that the regional groundwater flow direction is to the south-southeast. Due to insufficient data, potentiometric contours could not be established for the northern part of the basin; however, the general trend of the water levels shown in Figure 4.6 indicates that the groundwater flow direction is towards the south-southwest. It should be noted that the established regional potentiometric surface map is an over simplification of the flow directions and conditions. Potentiometric surface data is included in Appendix D-3.

## 4.3 Aquifer Test Programme

Two aquifer tests were conducted under the auspices of Environment Canterbury during the course of this study. Aquifer tests were conducted to determine aquifer transmissivity, storativity and hydraulic conductivity. In addition, data and analysis results from an aquifer test conducted by McMillan Water Wells is presented. Test sites were chosen based on regional location and accessibility, and are shown in Figure 4.8.

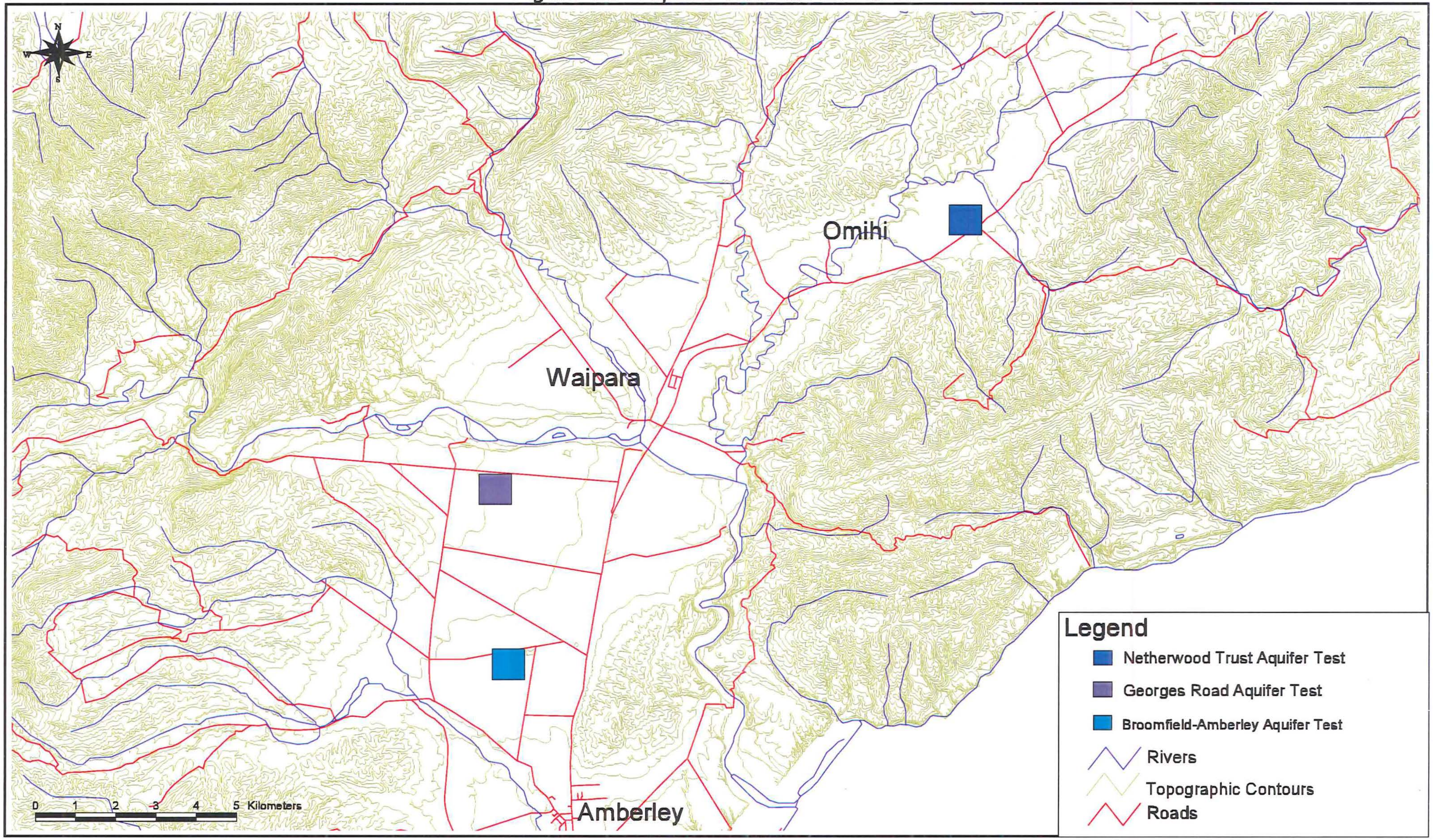
### 4.3.1 Previous Work

Prior to this study, no constant discharge tests were carried out in the region. Many of the wells that have been drilled in the last five years have undergone single well tests to determine the safe yield. The single well tests involved pumping a well for 24 hours in order to evaluate the well yield, drawdown, and specific capacity. While this test may be effective in determining the safe yield for the well, it does not evaluate aquifer characteristics (i.e. transmissivity, storativity and hydraulic conductivity), and more importantly, it does not evaluate the adverse effects on surrounding wells. The aquifer tests presented in this study are the first 24-hour constant discharge aquifer tests completed with observation wells in the Waipara Region.

### 4.3.2 Pump Test Methodology and Data Analysis

Prior to each aquifer test, water levels in the pumping well and the observation wells were measured on a daily basis for up to five days prior to testing to establish any antecedent trends. A pre-test was conducted prior to the pumping test in order to

*Figure 4.8 - Aquifer Test Site Locations*



establish a safe pumping rate to avoid pumping the well dry. Observation wells were measured manually with a water depth probe with millimetre precision. Wells that were thought to be too far away to be affected by early time pumping, or thought to be penetrating a different aquifer were monitored periodically throughout the test, after the first 5 hours of pumping. Chemical samples were taken near the beginning and end of the tests to identify changes in the water chemistry, which would indicate groundwater contributions from other sources (i.e. semi-confining units and/or additional aquifers). The discharge rate was measured throughout the test by use of a staff gauge (pressure readings) and orifice, in conjunction with a stopwatch and 10-litre bucket.

Aquifer tests were conducted under the following assumptions as outlined by Kruseman and de Ridder (1990) and Fetter (1994):

1) The aquifer is bound on the bottom by a confining layer.
2) All geologic formations are horizontal and of infinite horizontal extent over the area influenced by the pumping test.
3) The potentiometric surface of the aquifer is not changing with time prior to the start of pumping.
4) All changes in the position of the potentiometric surface are due to the effect of the pumping well alone.
5) The aquifer is homogeneous, isotropic and of uniform thickness.
6) All flow is radial towards the well.
7) The pumping well and observation wells are screened only in the aquifer being tested.
8) The pumping well and the observation wells are fully penetrating (i.e. they are screened over the entire thickness of the aquifer); and the pumping well receives water from the entire thickness of the aquifer by horizontal flow.
9) The water removed from storage is discharged instantaneously with decline of head.
10) The aquifer being tested is pumped at a constant rate.

The accuracy of the methods used to model the response of the drawdown in the observation wells is dependent upon the test conditions and on the number of assumptions that are fulfilled. The number of assumptions not satisfied limits the validity of the results and the interpretation. The accuracy of the pump tests conducted in this study is limited by the assumption that the well is fully penetrating, and that the well screens extend across only the aquifer being tested. Most Waipara wells tend to be screened over several thin water-bearing units, and/or are screened only along a portion of an aquifer because of financial limitations.

Prior to calculation of aquifer parameters, effects of tidal, barometric and antecedent trends were assessed. Tidal effects did not influence any of the time-drawdown data as tests were conducted approximately 10-20 kilometres inland from the coast, and therefore, no hydraulic connection is observed. In addition, barometric effects were not taken into account. Barometric pressure effects are typically observed in high-porosity semi-confined aquifers of great thickness (Brooks, 1997). Interpretation of well logs, and analysis of drill cuttings suggest that the aquifers are not highly porous and are relatively thin water-bearing units.

During all pump tests, steady state conditions were never reached, and therefore, all data are analysed by methods representing unsteady-state conditions. Several methods of analyses were applied, which produced a range of values for transmissivity, storativity and hydraulic conductivity, which were then compared with one another to determine the most representative value of the hydrogeologic conditions. Methods employed include the Theis curve-fitting and Jacob straight-line methods for confined aquifer conditions. The Hantush curve fitting method was used for semi-confined aquifer conditions with a compressible confining layer, and the Walton Method was used for semi-confined conditions with an incompressible confining layer. In addition, recovery data was analysed using the Theis recovery method. Analyses were completed manually, as well as with the computer software programme AQTESOLV, version 2.10.

## *4.4 Georges Road Aquifer Test – M34/0689*

### 4.4.1 Test Configuration and Conditions

The objective of this aquifer test was to determine the transmissivity and storativity values as well as the spatial extent of a 24 to 30 metre deep aquifer located south of the Waipara River on Georges Road, approximately 6 km west of State Highway 1 (Figure 4.8). Figure 4.9 shows the aquifer test configuration wells and groundwater flow direction. The dashed contours and arrows indicate the flow direction for the pump test wells. Solid contours and arrows indicate the direction of the other wells in the subdivision. Groundwater flow is in a south-easterly direction. *Table 4.2* provides information about the pumping well and observation wells. Examination of the well logs suggests that the aquifer is a semi-confined to confined aquifer, and of variable thickness. The aquifer being tested, according the driller's log is composed of 'tight water-bearing gravel' with clay seams. Well screens are typically 4 - 6 metres long, and in some instances (i.e. M34/0689 and M34/0688) the well screens extend across two lithologically distinct water-bearing units. A cross-section of the Georges Road wells is presented in Figure 4.10. Aquifers have been treated as a single unit in order to satisfy the assumption that the aquifer being tested is homogeneous and isotropic.

**Table 4.2 – Georges Road Aquifer Test Well Details**

| Well No. | Use[1] | Depth (m) | Yield[2] (l/s) | Aquifer Thickness (m) | Screen Interval | Static Water Level (mbgl) | Well Status during Aquifer Test |
|---|---|---|---|---|---|---|---|
| M34/0689 | Ir/Do | 24.80 | 1.16 | 4 | 20.20 – 24.20 | -11.653 | Pumping |
| M34/0688 | Ir/Do | 27.65 | 0.25 | 6.5 | 21.65 – 27.65 | - 9.277 | Observation |
| M34/0690 | Ir/Do | 26.15 | 0.89 | .6 | 22.15 – 26.15 | - 9.005 | Observation |
| M34/0691 | Ir/Do | 22.60 | 0.67 | 4 | 18.60 – 22.60 | - 9.873 | Observation |

[1] Ir = irrigation, Do = domestic
[2] reported by driller

The test was conducted from the 27$^{th}$ – 28$^{th}$ May 1999. Well M34/0689 was chosen as the pumping well because of its central location and it is the highest yielding well of the group. A submersible pump was installed and pumped for a total of 22.5 hours at approximately 2.25 l/s. The test was intended to run for 24 hours, however, the test was terminated after 22.5 hours of pumping because the drawdown never reached a steady state, and the drawdown in the well continued to decline putting the pump in

*Figure 4.9 -Georges Road Pump Test Site Configuration and Groundwater Flow Map*

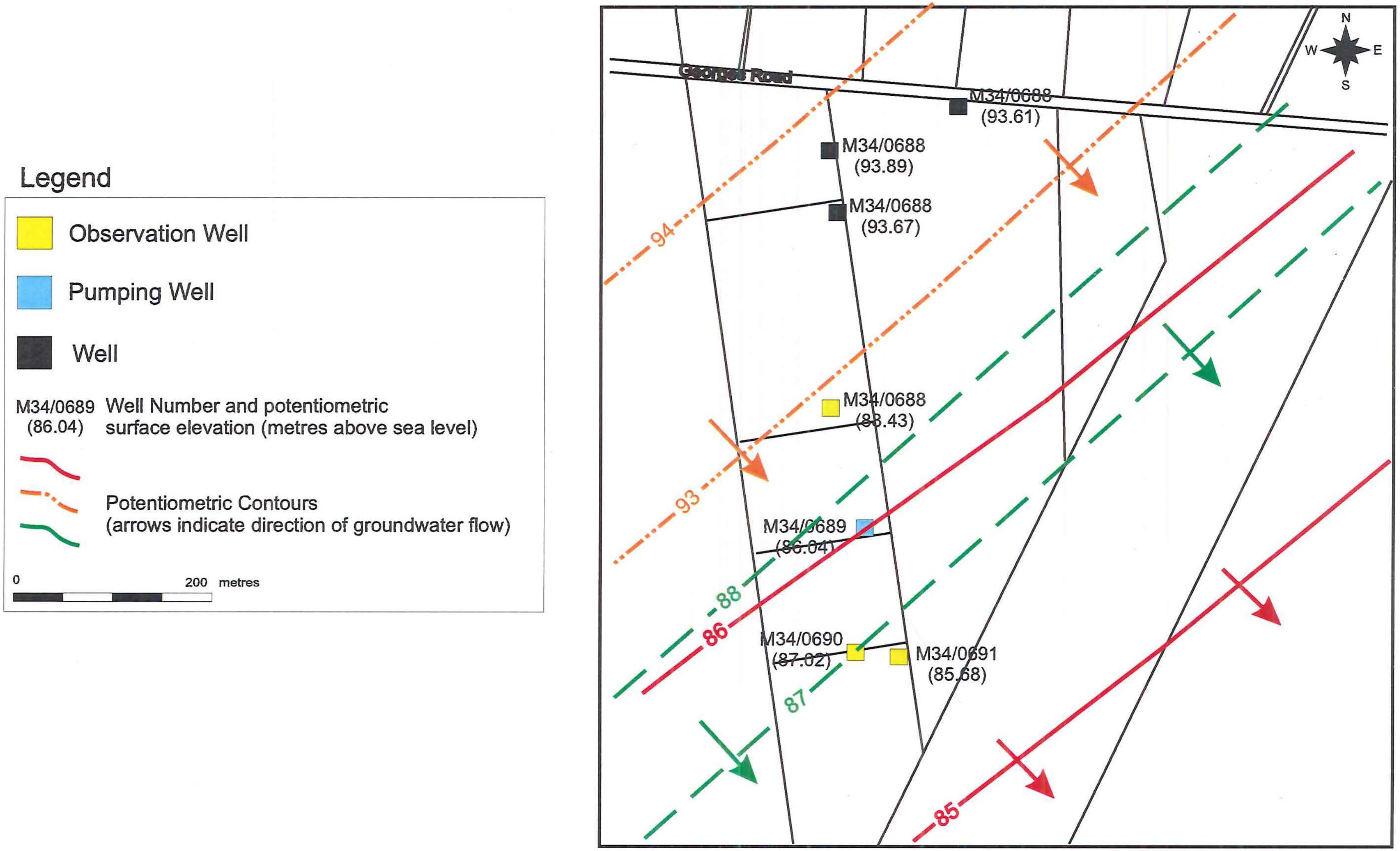
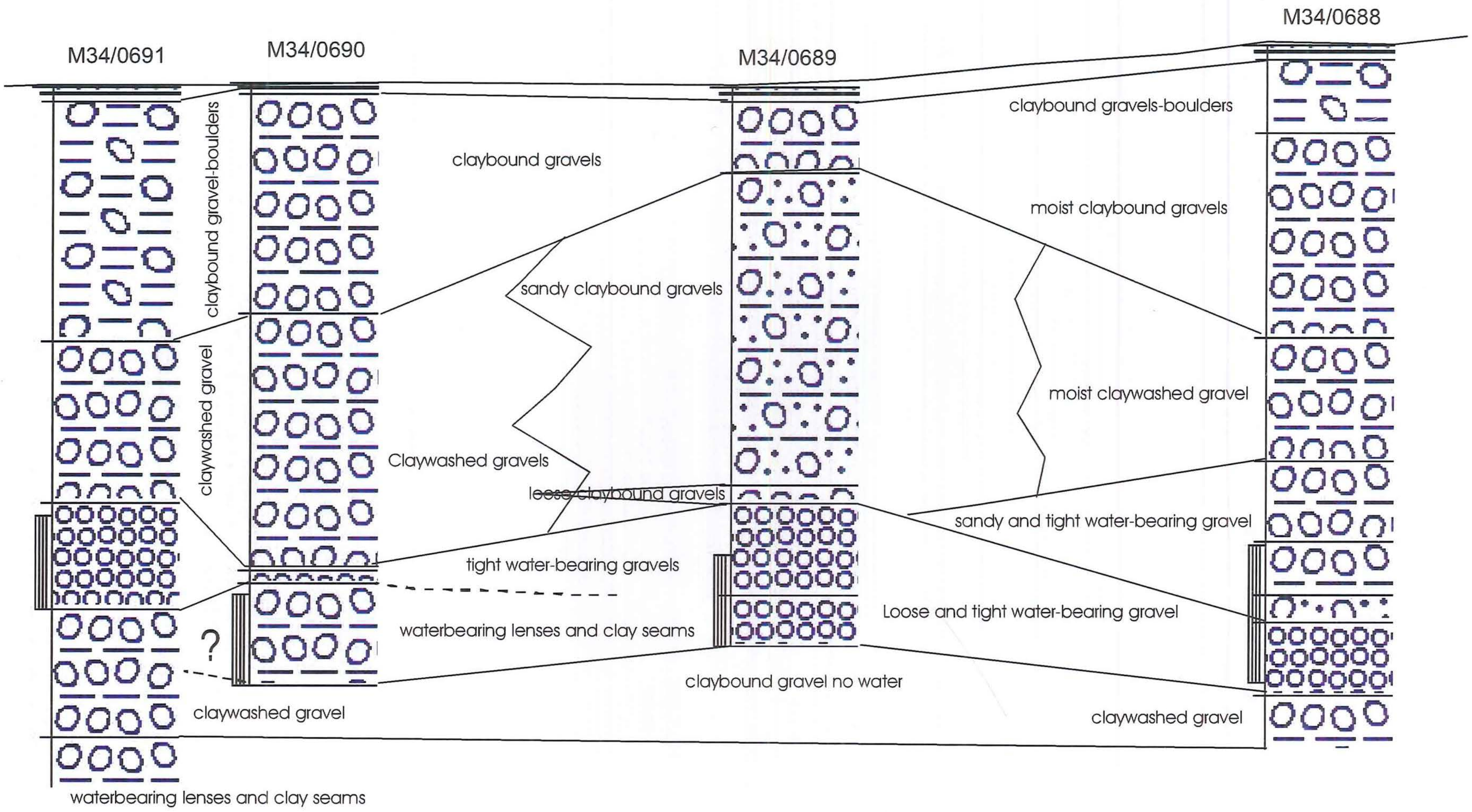


**Figure 4.10 -Stratigraphic Cross-Section (D-D') of Georges Road AquiferTest Wells**



jeopardy. The water was discharged 100 metres downgradient in a south-easterly direction from the pumping site through a series of fire hoses (Figure 4.11). After the cessation of the pump test, the recovery was monitored in all four wells until each of the wells had recovered by 80%.

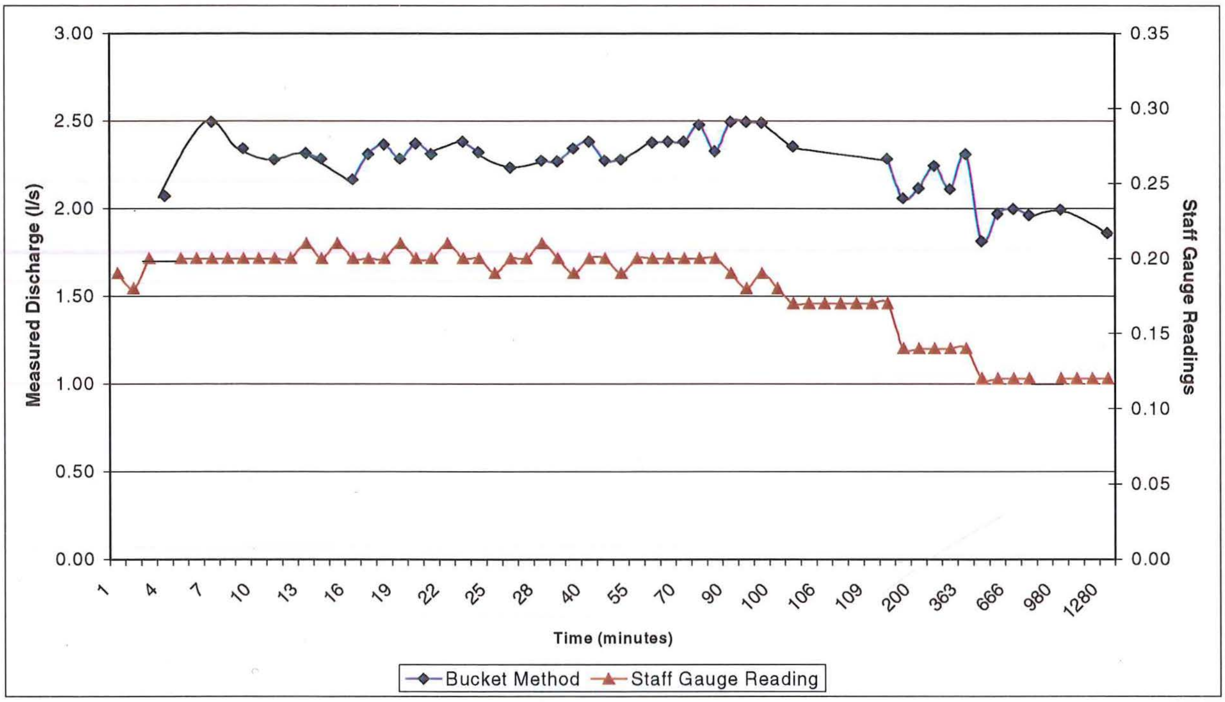
***Figure 4.11 – Apparatus constructed to discharge and measure water pumped from M34/0689 during the Georges Road Aquifer Test. The bucket (foreground) and staff pressure gauge were used to monitor the discharge rate.***

### 4.4.2 Aquifer Test Data and Analysis

#### *4.4.2.1 Sources of Error*

The primary sources of error were most likely due to the difficulty in maintaining a constant pumping rate throughout the pump test, and measurement errors in the observation wells. Human error is estimated to be no greater than 1 cm, as water levels were measured to the millimetre. Figure 4.12 shows the variation in the discharge rate throughout the aquifer test. After 100 minutes of pumping, the discharge rate began to decline, and several adjustments were made in an attempt to restore the pumping rate. The drawdown in the pumping well did not reach equilibrium, and therefore the water

***Figure 4.12 - Discharge Rate Variability During Georges Road Aquifer Test***



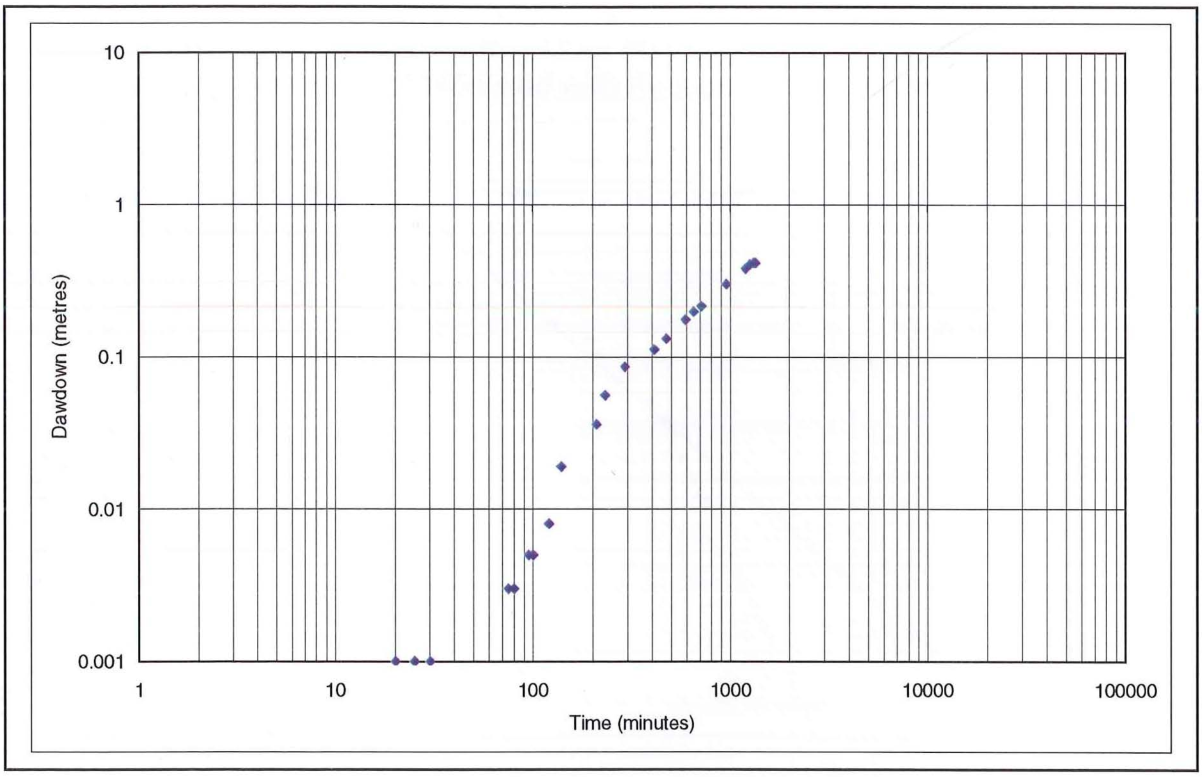

level continued to drawdown throughout the test, resulting in the termination of the test at 22.5 hours. The average pumping rate during the test was 2.26 l/s (194 $m^3$/day). The total reduction in the pumping rate from the start of the test to the end was approximately 12%.

### *4.4.2.2 Data Analysis*

All aquifer test data, analysis plots, records of measured antecedent trends, and other related data are included in Appendix 4G. Initial observed drawdowns began at 35 (M34/0691), 70 (M34/0690) and 95 (M34/0688) minutes after the start of the test. The elapsed time between the start of the test and the start of drawdown in the observation wells, suggests that the aquifer transmissivity and storativity are low. M34/0691 is the furthest from the pumping well and responded first, whereas M34/0688, which was closest to the pumping well, responded last, reflecting the heterogeneity and anisotropy of the hydrogeological conditions. In addition, M34/0691, located the furthest distance from the pumping bore (223 metres), exhibited the highest total drawdown (1.146 m). Wells M34/0688 and M34/0690 located approximately 200 metres from the pumping well, exhibited maximum drawdowns of 0.415 and 0.452 metres, respectively. Based on the above observations, several of the assumptions are not satisfied.

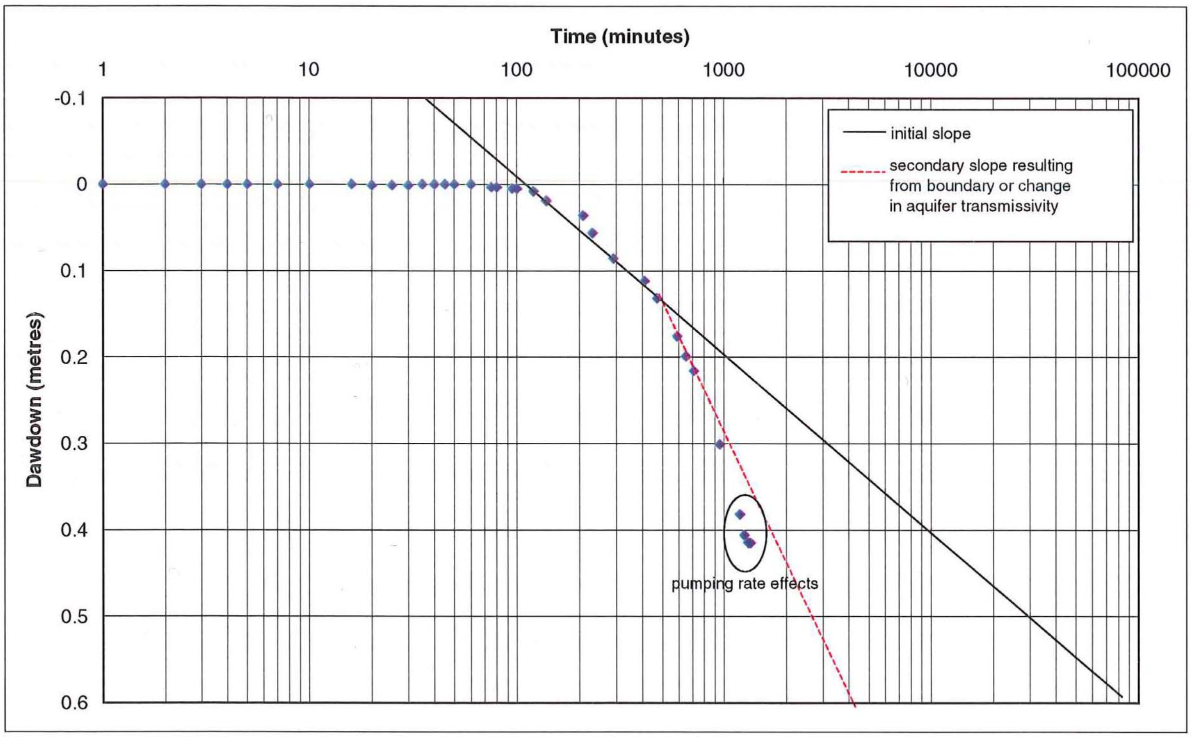
Time-drawdown data from M34/0688 are anomalous. Inspection of the bore log for well M34/0688 indicates that the well is screened over three lithologically distinct water-bearing units. Early--time data from M34/0688 does not follow the characteristic Theis curve for a log-log plot, and appears to form a straight-line segment of the graphed data, suggesting the presence of a boundary condition. The small drawdown observed in M34/0688 may indicate that of the screened portion of the aquifer does not have a good hydraulic connection to the pumped aquifer, and/or there is a decrease in aquifer transmissivity towards M34/0688 (Figure 4.13a).

***Figure 4.13a – Time-Drawdown Log-Log Plot for M34/0688***




Intermediate-time data appears to have been affected by adjustments of the discharge rate, and late-time data begins to resemble the characteristic time-drawdown curve. The effect of the decrease in discharge can be seen at the end of the late-time data as the last two points begin to decrease in slope. This type of deviation from the theoretical curve may be a response to the effects of well-bore storage, which typically occurs during large-diameter pumping test where the well storage capacity is high, or pumping rates are sufficiently low. Variations in the discharge rate at the beginning of the test are reflected in the offset of the data points at between 150 and 200 minutes. The semi-log plot of time-drawdown data (Figure 4.13b) shows a change in slope between t = 500 - 600 minutes, and indicates a low permeable boundary. The apparent change in slope suggests a decrease in the aquifer transmissivity attributable to an increase in clay or silt content in the aquifer or the aquifer or the presence of a clay lens (Driscoll, 1990). The bore log for well M4/0687, located immediately north of M34/0688 shows a similar gravel-type aquifer, but the suggested aquifer yield decreases to 0.18 l/s, indicating a decrease in aquifer permeability towards M34/0687. Time-drawdown data for M34/0690 exhibit a similar response during the test to M34/0688, indicating similar hydrogeological conditions (Appendix D-4).

***Figure 4.13b – Time-Drawdown Semi-Log Plot for M34/0688 Illustrating the Effects of Boundary Conditions Associated with Reductions in Aquifer Transmissivity***




Time-drawdown data did not require corrections for tidal, barometric or antecedent trends (Appendix D-4).

Chemical analyses of samples taken of the discharging groundwater at the beginning and end of the aquifer test do not show any significant deviations suggesting that the recharge source is the same throughout the test.

### 4.4.3 Analysis Results and Discussion

Table 4.3 provides a summary of the aquifer test results (i.e. method of analysis, maximum drawdown and suggested aquifer yield, duration of recovery, and calculated aquifer parameters). Time-drawdown data and recovery data from M34/0688, M34/0690, and M34/0691, were analysed using several methods to determine transmissivity, storativity and hydraulic conductivity. Analyses for confined and semi-confined conditions yield similar values for transmissivity, storativity and hydraulic conductivity. This suggests that semi-confining layers exhibit hydraulic properties more representative of confining units, and contributions from overlying confining layers are negligible (i.e. β-values, the leakage coefficient and r/L determined from the Hantush and Walton methods are indistinguishable from the Theis Curve).

The most obvious discrepancies are between the calculated values from the recovery method and the other methods, particularly for M34/0688 and M34/0690. Values obtained from the Jacob method are unreliable because the time-drawdown data does not satisfy the limiting condition ($u < r^2S/4Tt$; $u < 0.01$) (Fetter, 1994). In addition, the transmissivity value calculated from time-drawdown data for observation well M34/0691 using the Hantush method is rejected based on examination of the semi-log plot, which does not exhibit the effects of leakage. For other wells analysed using the Hantush method, the limiting condition ($t < S'D'/10K$) is not satisfied, and results show that that the best-fit curve is indistinguishable from the Theis curve (i.e. $\beta = 1 \times 10^{-5}$). Discrepancies between calculated values from the Theis manual solution method, AQTESOLV and the Walton method compared with those calculated from the recovery method is most likely the result of pumping rate fluctuations distorting the early-time data. Distortion of the early time data resulted in modelling of the later-time data. Results from observation well M34/0690, although in agreement with the other calculated values, is peculiar given that the pumped aquifer thins to 0.6 metres. A decrease in aquifer thickness would result in a decrease in the transmissivity, assuming the permeability of the aquifer was constant. However, the opposite effect occurs, and has been interpreted to indicate that the underlying aquifer is also hydraulically connected to the tested aquifer.

### *Table 4.3 – Summary of Results from Georges Road Pump Test*

| *Well Number* | *Maximum Drawdown (metres)* | *Calculated Aquifer Parameters* | | |
|---|---|---|---|---|
| | | *Transmissivity ($m^2$/day)* | *Storativity* | *Hydraulic Conductivity (m/day)* |
| **M34/0688** | 0.415 | | | |
| Theis | | 36 / 38* | .0009 / .0007 | 5 - 6 |
| Jacob | | 40 | .0005 | 6 |
| Hantush | | 36 | .0009<br>$\beta = 1 \times 10^{-5}$ | 5 |
| Walton | | 30 | .0007<br>r/L = 0 | 5 |
| Recovery | (t > 38 hours) | 9 | | 3 |
| **M34/0690** | 0.452 | | | |
| Theis | | 34/36* | .0006 / .0007 | 8-9* |
| Jacob | | 43 | .0008 | 10 |
| Hantush | | 36 | .0007<br>$\beta = 1 \times 10^{-5}$ | 8 |
| Walton | | 35 | .0006<br>r/L = 0 | 9 |
| Recovery | (t = 25 hours) | 22 | | 5 |
| **M34/0691** | 1.146 | | | |
| Theis | | 22/23* | .0002 | 5 |
| Jacob | | 30 | .0001 | 7 |
| Hantush | | 15 | .0001<br>$\beta = .15 \times 10^{-5}$ | *8* |
| Walton | | 24 | .0002<br>r/L = 0 | 5 |
| Recovery | | 22 | | 5 |
| **M34/0689**<br>Recovery | (t = 27 hours) | 15 | | 4 |

The best method of analysis was the recovery method, which eliminated the effects of a fluctuating pumping rate, and effects associated with the efficiency of the well and pump. Based on calculated values from the recovery method, the aquifer test results show an increase in aquifer transmissivity and storativity to the south (M34/0690 and M34/0691), and a decrease in aquifer transmissivity to the north (M34/0688). The change in aquifer transmissivity is not clearly exhibited in semi-log time-drawdown plots or in the recovery data. The time-drawdown curves observed in the Georges Road aquifer test demonstrate the hydrogeologic variability, and result in a range of values for aquifer transmissivity, storativity and hydraulic conductivity. Aquifer transmissivity in this area ranges from 9 to 24 $m^2$/day, and the hydraulic conductivity ranges from 3 – 8 m/day, which is in good agreement with theoretical values for gravel aquifers composed of gravel and sand mixes as shown in Table 4.4 (Kruseman and de Ridder, 1990). Time-drawdown data shows that aquifer storativity is low, as indicated by the steep cone of depression representative of low transmissivity, the elapsed time between the start of the test and observed drawdown, and the long recovery times. The low transmissivity values are representative of the nature of the aquifer lithology and thickness. The observed drawdown responses demonstrate that two water-bearing units exhibiting distinct lithologies may be hydraulically connected, and therefore, pump tests are invaluable for determining the adverse affects between neighbouring wells.

***Table 4.4 – Estimated Values of Hydraulic Conductivity for Unconsolidated Rocks (modified from Kruseman and de Ridder, 1990)***

| Geological classification | K (m/d) |
|---|---|
| Unconsolidated materials: | |
| Clay | $10^{-8} - 10^{-2}$ |
| Fine sand | $1 - 5$ |
| Medium sand | $5 - 2 \times 10^{1}$ |
| Coarse sand | $2 \times 10^{1} - 10^{2}$ |
| Gravel | $10^{2} - 10^{3}$ |
| Sand and gravel mixes | $5 - 10^{2}$ |
| Clay, sand, gravel mixes (e.g. till) | $10^{-3} - 10^{-1}$ |

## 4.5 Broomfield-Amberley Aquifer Test – M34/0659

### 4.5.1 Test Configuration and Conditions

The Broomfield-Amberley aquifer test was conducted on October 20th 1999. The objective of this aquifer test was to determine aquifer parameters for a group of wells located in a subdivision on Racecourse and Stanton Roads in the Broomfield-Amberley area (Figure 4.8). Figure 4.14 shows the test configuration (i.e. the location of the pumping well, observation bores and other neighbouring wells), as well as groundwater flow direction. Table 4.5 provides details about the pumping well and observation wells. Examination of the well logs suggests that the aquifer is semi-confined and of variable thickness (Figure 4.15). The tested aquifer is described by the driller's log as being composed of 'good clean gravels.' However, it is suspected that the aquifer contains considerable amounts of silt and fine sand, which can often be washed out during the drilling process, thereby explaining the low aquifer yields. Well screens are typically 2 - 3 metres long, and do not extend along the entire length of the aquifer.

Well M34/0659 was chosen as the pumping well because of its central location. A submersible pump was installed and pumped for a total of 21.5 hours at approximately 2.0 l/s. The test was intended to run for 48 hours. However, drawdown in the pumping well never reached equilibrium, and continued to decline putting the pump in jeopardy.

***Table 4.5 - Aquifer Test Well Details***

| Well No. | Use[1] | Depth (m) | Yield (l/s | Aquifer Thickness (m) | Screen Interval (m) | Static Water Level (mbgl) | Well Status during Aquifer Test |
|---|---|---|---|---|---|---|---|
| M34/0659 | Do/St | 28.0 | 0.45 | 9.0 | 26.5 – 28.0 | -4.790 | Pumping |
| M34/0660 | Do/St | 24.0 | 0.50 | 4.0 | 22.5 – 24.0 | -5.046 | Observation |
| M34/0704 | Do/St | 24.0 | 0.50 | 6.0 | 22.0 – 24.0 | -5.583 | Observation |
| M34/0666 | Do/St | 24.0 | .38 | 4.2 | 22.5 – 24.0 | -4.590 | Observation |
| M34/0667 | Do/St | 24.0 | .45 | 13.5 | 22.5 – 24.0 | -4.687 | Observation |
| M34/0661 | Do/St | 24.6 | .45 | No log | 22.5 – 24.0 | -3.530 | Observation[2] |
| M34/0662 | Do/St | 23.0 | .38 | 4.5 | 21.5 – 23.0 | -3.610 | Observation[2] |

[1] Do = domestic, St = stock. [2]Observed after 5 hours of pumping;

***Figure 4.14 - Broomfield-Amberely Aquifer Test Site Configuration and Potentiometric Surface***

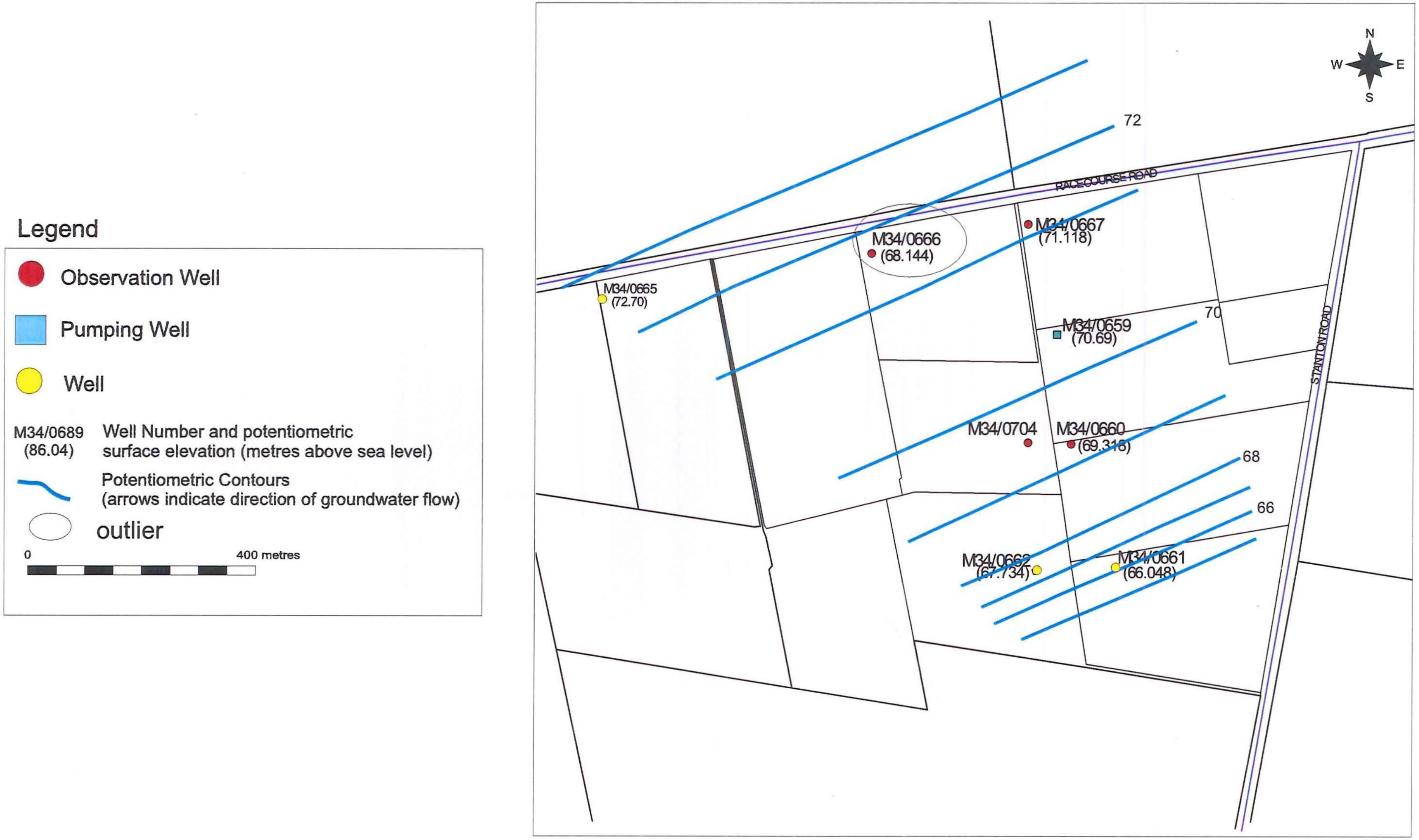
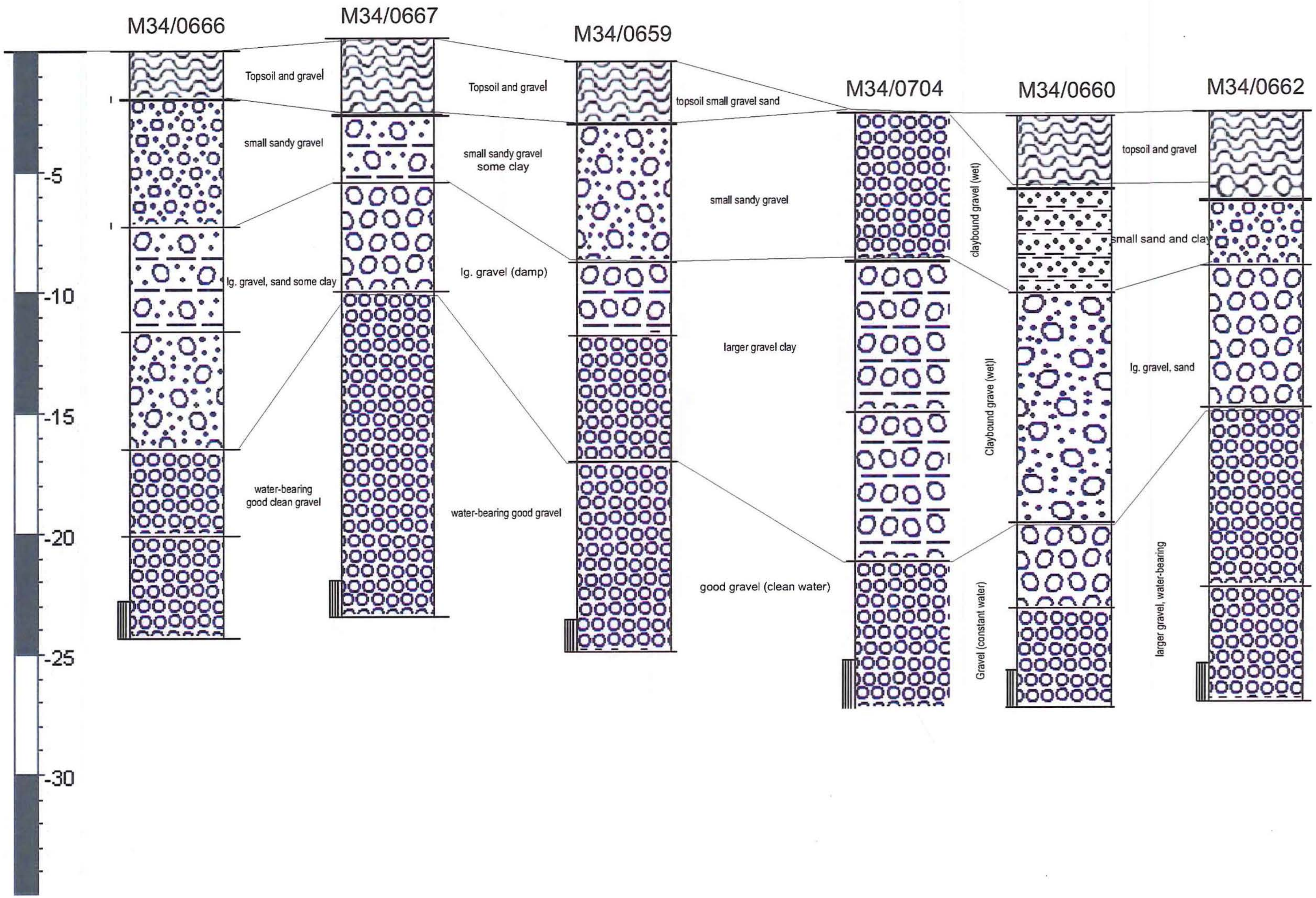


***Figure 4.15 - Stratigraphic Cross- section(E-E') of Broomfield-Amberley Aquifer Test Wells***



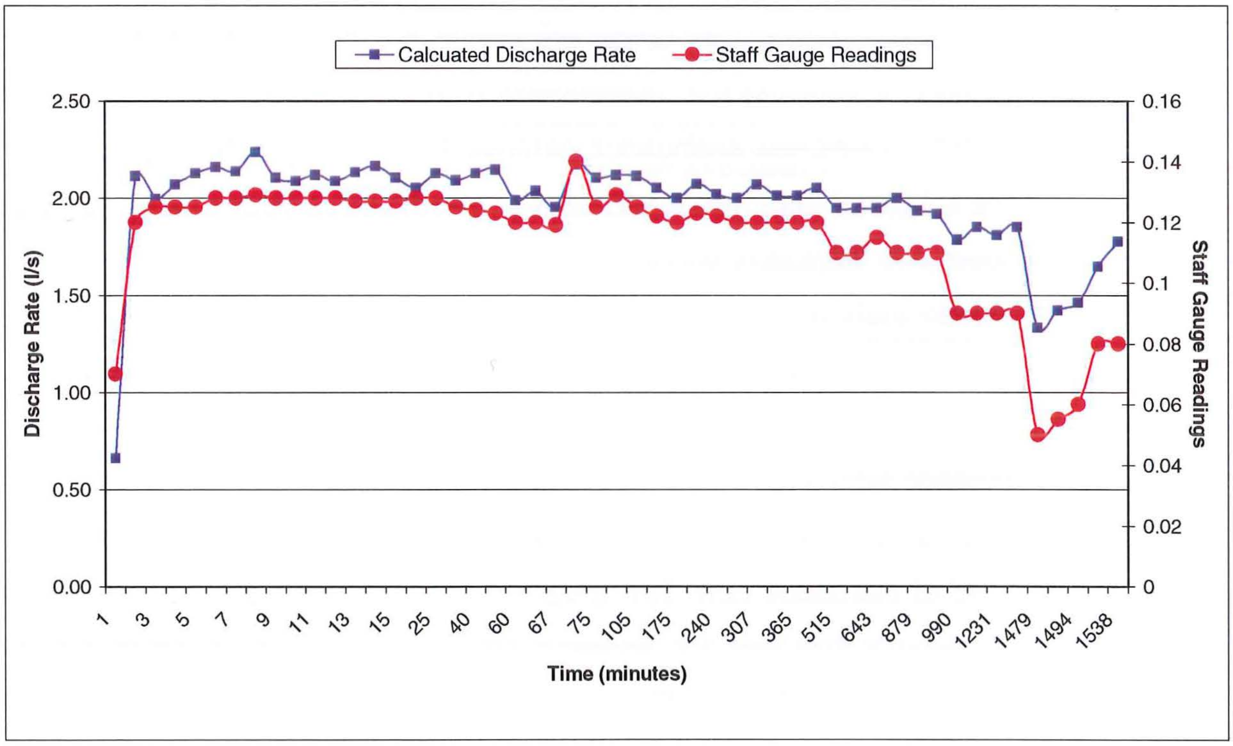
The water was discharged 100 metres downgradient from the pumping site through a series of fire hoses. Well recovery was monitored until each of the wells had recovered by 80%. Chemical samples were taken during the beginning and end of the test to identify changes in water chemistry, which may be indicative of additional recharge sources (i.e. semi-confining layer or another aquifer).

### 4.5.2 Aquifer Test Data and Analysis

#### *4.5.2.1 Sources of Error*

The main sources of error were most likely attributed to variations in pumping rate and measurement errors of water-level drawdown in the observation wells. Figure 4.16 shows the variation in the discharge rate throughout the aquifer test. The measured

***Figure 4.16 – Discharge Rate Variability During Broomfield-Amberley Aquifer Test***




discharge showed fluctuations throughout the entire test, and may be the result of the techniques used to measure the discharge rather than actual variations in pumping rate. Use of an orifice and staff pressure gauge for measuring the discharge may not be the most appropriate method for measuring the discharge during low-flow pumping tests because of the lack of pressure and additional pressure losses as the water is discharged through 100 metres of hose to the orifice. An overall decline in the discharge rate is apparent after t =360 minutes, and is attributable to the pumping equipment, which has to work harder under a declining pressure head, resulting in a gradual decline in the pumping rate. In addition, adjustments in the pumping rate were made after 960 minutes into the test to prevent the drawdown in the pumping well from falling below the pump. An additional adjustment was made again at 1490 minutes. The drawdown in the pumping well never reached equilibrium and the water level continued to drawdown throughout the test, resulting in the termination of the test at 22.5 hours. The average pumping rate during the test was 1.97 l/s (170 $m^3$/day). The deviation from the average discharge rate throughout the test was approximately 7.8%.

#### *4.5.2.2* Data Analysis

Aquifer field records, test data, and details of analyses are included in Appendix D-5. Time-drawdown data collected during the pump test from all observation wells are of poor quality in terms of quantitative assessment, but provides a good illustration of the hydrogeologic heterogeneity and variable subsurface conditions. Data from M34/0704 could not be analysed as the resulting time-drawdown data formed a straight line when plotted on a log-log graph, and is interpreted to be indicative of a boundary condition (Figure 4.17). Further evidence of the existence of a boundary condition is provided from the time-drawdown data from M34/0666 (Figure 4.18).

Well M34/0666 is 280 metres from the pumping well, with a total observed drawdown of 6 mm. The water level fell an additional 4 cm over the next 48 hours. Well M34/0661, located 360 metres away from the pumping well, was supposed to be used to monitor antecedent trends throughout the test, however, the well was affected by pumping, and exhibited a total drawdown of 0.688 metres. The resulting drawdown in M34/0666 is interpreted as the effects of antecedent trends rather than pumping effects. The drawdown responses of M34/0666 and M34/0704, suggest that the boundary is most likely located to the west of the pumping well.

Time-drawdown data for M34/0667 and M34/0660 exhibited boundary conditions. The semi-log plot for M34/0667 (Figure 4.19) shows three changes in slope of the time-

***Figure 4.17 –Time-Drawdown Log-Log Plot for M34/0704***

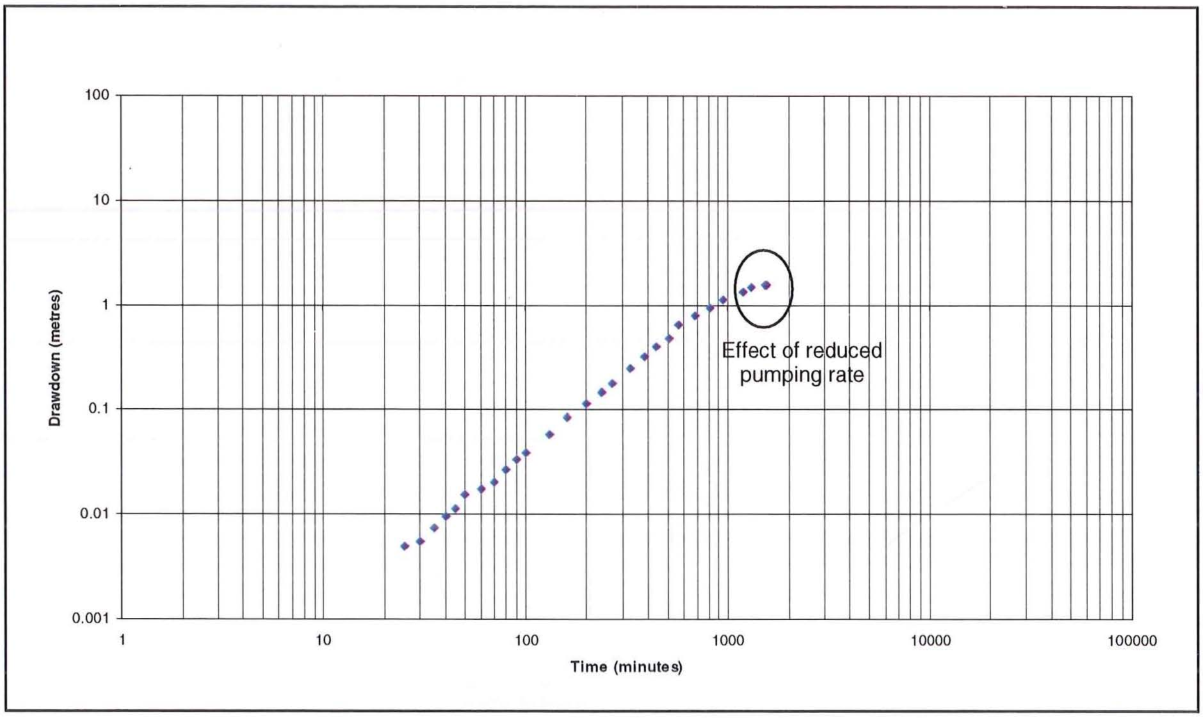



***Figure 4.18 – Observed Drawdown in M34/0666 throughout Aquifer Test***

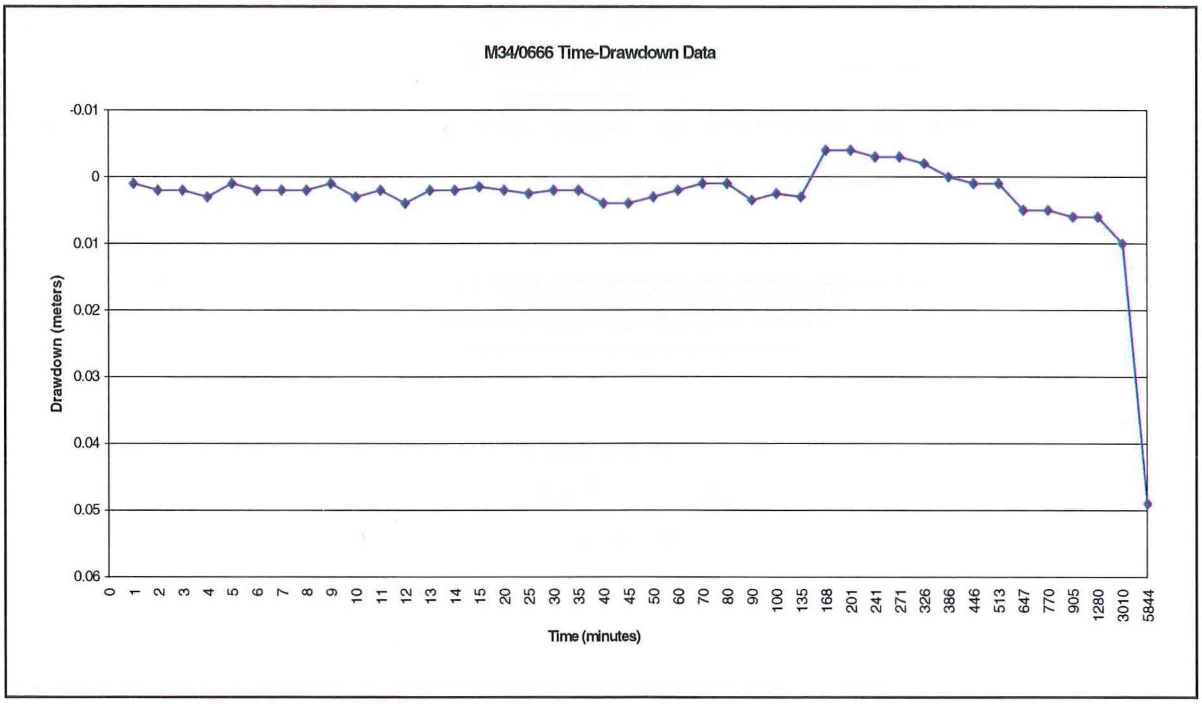
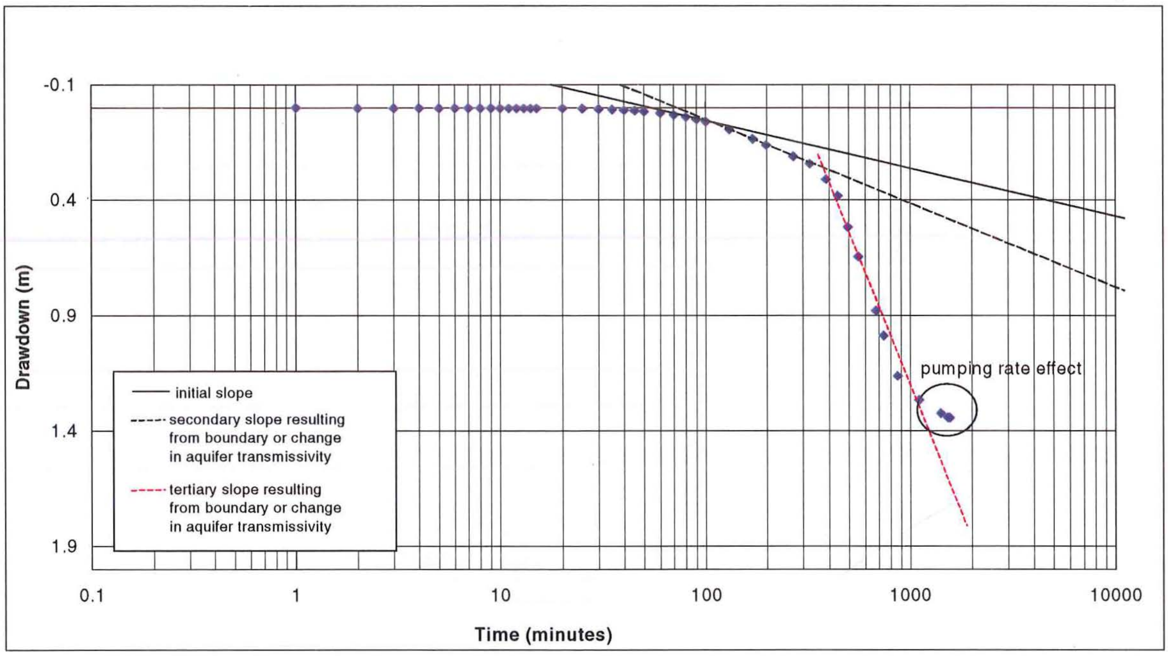
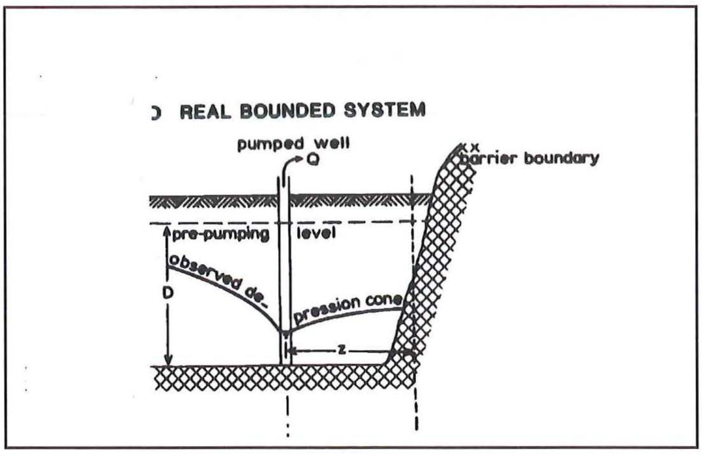


***Figure 4.19 –Time-Drawdown Semi-Log Plot for M34/0667 Illustrating the Effects of Boundary Conditions Associated with Reductions in Aquifer Transmissivity***




drawdown curve, indicating a decrease in aquifer transmissivity, with increasing distance from the pumping well. The decrease in slope at t = 1000 minutes is attributed to the reduction in pumping rate at the end of the test. Both M34/0667 and M34/0660 are similar distances from the pumping well, but the resulting drawdowns differ by a metre, demonstrating heterogeneous and anisotropic hydrogeological conditions (Table 4.6). In addition, the greater observed drawdown in M34/0660 suggests that the boundary condition may be located closer to M34/0660 as the presence of an impermeable boundary condition will cause a greater drawdown in the well closest to the boundary as shown in Figure 4.20.

***Figure 4.20 – Effects of a Barrier Boundary on Drawdown During Pumping (Kruseman and de Ridder, 1990)***



Aquifer parameters for all wells exhibiting boundary conditions or anomalous time-drawdown data were analysed using the recovery method as outlined by Kruseman and de Ridder (1990).

Monitoring wells M34/0661 and M34/0662 produced similar time-drawdown curves (Appendix D-5) and were not affected by boundary conditions, suggesting that a low transmissivity zone within the aquifer was encountered before the cone of depression reached M34/0661 and M34/0662. Both the wells are approximately 350 metres from the pumping well and should have similar drawdowns, however, the drawdown in M34/0662 is 0.4 metres greater than the drawdown in M34/0661. The observed difference in the drawdown between the two wells reflects a decrease in aquifer thickness and/or aquifer permeability. No log exists for M34/0661, and therefore, the cause cannot be determined.

### 4.5.3 Aquifer Test Results and Discussion

Calculated results are presented in Table 4.6. Evaluation of aquifer parameters for all observation wells (except M34/0666 and M34/0704) was completed with the recovery method. In addition, time-drawdown data for M34/0661 and M34/0662 were analysed using the Theis method, particularly to evaluate the storativity, which cannot be determined from the analysis of recovery data. The Jacob method was not used because the limiting condition $u < 0.01$ was not satisfied. It is recognised that the time-drawdown data for M34/0661 and M34/0662 are missing the early-time data, and that the calculated values may be slightly lower than expected. Comparison of calculated values enables the identification of anomalies, and to determine most representative method of analysis for the given hydrogeological conditions. Semi-confined analyses were not used because of the difficulty in constraining the type curves as the test was terminated before leakage effects are most likely to occur.

The calculated values of transmissivity, storativity and hydraulic conductivity are in good agreement with each other, except for the calculated transmissivity value for the pumping well (M34/0659). The anomalous value is most likely the result of errors in measurement of the early-time recovery data. The overall quantitative results show that

***Table 4.6 – Summary of Results from Broomfield-Amberley Pump Test***

| *Well Number* | *Distance to Pumping Well (metres)* | *Maximum Drawdown (metres)* | *Boundary Observed (t= min)* | *Calculated Aquifer Parameters* | | |
|---|---|---|---|---|---|---|
| | | | | *Transmissivity ($m^2$/day)* | *Storativity* | *Hydraulic Conductivity (m/day)* |
| **M34/0666** | 311 | 0.006 | | *ND* | *ND* | *ND* |
| **M34/0704** | 196 | 1.550 | 15 | | | |
| Recovery | | | | 15 | *NA* | 3 |
| **M34/0662** | 344 | 1.050 | *NO* | | | |
| Theis | | | | 10 | .0001 | 2 |
| Recovery | | | | 20 | *NA* | 4 |
| **M34/0661** | 369 | 0.650 | *NO* | | | |
| Theis | | | | 12 | .0002 | *ND* |
| Recovery | | | | 23 | *NA* | *ND* |
| **M34/0660** | 176 | 2.129 | 15 | | | |
| Recovery | | | | 13 | *NA* | 3 |
| **M34/0667** | 168 | 1.344 | 15 | | | |
| Recovery | | | | 16 | *NA* | 1 |
| **M34/0659** | | 19.96 | *NO* | | | |
| Recovery | | | | 4 | *NA* | .4 |

**NO* – Not Observed, *ND* – No Data, *NA* – Not applicable the transmissivity is low, storativity is low and the hydraulic conductivity is low. Chemical analyses show that the water chemistry and clarity of the water changed sometime after 500 minutes of pumping. The change in water colour is most likely attributed to sediment collapse in the vicinity of the well due to dewatering of the aquifer. The Broomfield-Amberley aquifer test demonstrates the importance of conducting a pump test to determine the adverse effects on neighbouring wells. Equally, it can prove that wells located at approximately the same depth in a small area may not necessarily be hydraulically connected, demonstrating the complex hydrogeological conditions. In addition, the pump test showed the spatial limitations of the aquifers with barrier boundary conditions observed only 15 minutes into the test. The transmissivity is extremely low given the reported aquifer thickness. The results show that the aquifer transmissivity increases to the south and north of the pumping well, suggesting the presence of a more transmissive zone bound by zones of low permeability and transmissivity. The long recovery times are typical in hydrogeologic systems where boundary conditions exist (Table 4.6), indicative of the limited available recharge and the inability of the aquifers to release water from storage. The estimated hydraulic conductivity is 3 m/day indicating that the aquifer is most likely a mixture of gravels and silt or clay, and questions the validity of the reported well log aquifer descriptions.

## *4.6 Netherwood Trust Aquifer Test – N34/0142*

### 4.6.1 Test Configuration and Conditions

The Netherwood Aquifer test was conducted by McMillian Water Wells and the well owner on November 11$^{th}$ 1999. Prior to the test, four wells had been drilled on the property (Figure 4.21), and the objective of the pump test was to determine the adverse effects on surrounding wells when pumping well N34/0142. Figure 4.21a shows the pumping test configuration. Groundwater flow is believed to be towards the south. The data was collected by the owner and McMillan's Water Wells. Analysis of the aquifer test data was completed by the writer. Wells M34/0134 and M34/0143 were monitored throughout the test. Table 4.7 provides information about the aquifer test well and observation wells.

Examination of the well logs suggests that the aquifer is a confined aquifer composed of 'brown clean and sandy gravels'. Well N34/0134 is screened over several thin water-

***Table 4.7 – Netherwood Trust Aquifer Test Well Details***

| Well No. | Use[1] | Depth (m) | Yield (l/s) | Aquifer Thickness (m) | Screen Interval | Static Water Level (mbgl) | Well Status during Aquifer Test |
|---|---|---|---|---|---|---|---|
| N34/0143 | Ir/St | 120.0 | 8.90 | 9.5 | 110.50 – 120.0 | 14. 80 | Observations |
| N34/0134 | Ir/St | 155.0 | 15.4 | 13.5 and 6.0 | 96.25 – 145.15 | 14.20 | Observation |
| N34/0142 | Ir/St | 149.0. | 22.85 | 12.0 and 6.0 | 96.50 – 110.0; 145.5 – 151.0 | 13.90 | Pumping |

[1] Ir = irrigation, St = stock

bearing units, and therefore, the assumption that the pumping well and observation wells are screened only in the aquifer being tested may not be valid, and calculated aquifer parameters will tend to reflect the higher yielding aquifer (Driscoll, 1986). The pumping well is screened in two places, and similar to well N34/0134, the screens extend across several thin water-bearing layers between 96.5 – 110.2 metres and 145.5 and 151.0 metres. A cross-section constructed from the groundwater well logs (Figure 4.21b), suggests that the wells are screened over the same aquifers. The pump was set at approximately 80 mbgl and pumped at 22.7 l/s. Like previous aquifer tests, the test was intended to run for 24 hours but was terminated after 22 hours and 20 minutes of pumping because of difficulties in maintaining the pumping rate. Recovery of the wells was not measured. The direction of groundwater flow cannot precisely be determined because the wells are screened over several aquifers, and therefore, the measured head represents the combined pressure heads of the individual water-bearing layers. Based on the surface topography and measured water levels, the flow direction is believed to be towards the south of the pumping site.

### 4.6.2 Aquifer Test Data and Analysis

#### *4.6.2.1 Sources of Error*

Errors were most likely attributed to difficulty in maintaining a constant pumping rate and measurement errors in the observation well. The discharge rate was constant until 615 minutes after pumping, and several adjustments were made in an attempt to restore the pumping rate. The average pumping rate was 22.5 l/s. Figure 4.22 shows thefluctuations in discharge throughout the test.

***Figure 4.21a- Netherwood Trust Aquifer test Site Configuration and Inferred Potentiometric Surface***

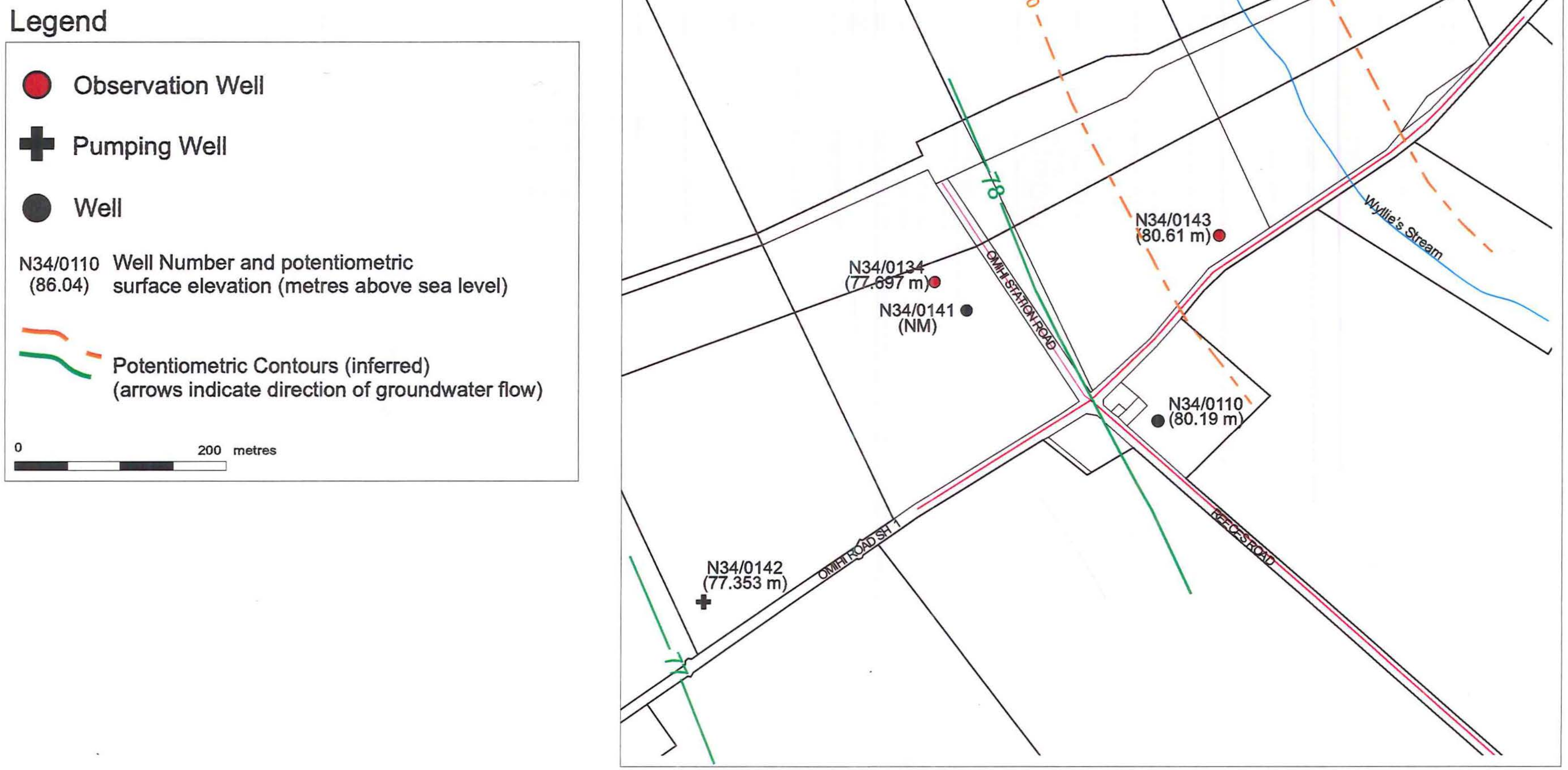


***Figure 4.21b- Cross-section (F-F') of Netherwood Trust Aquifer Test Wells***

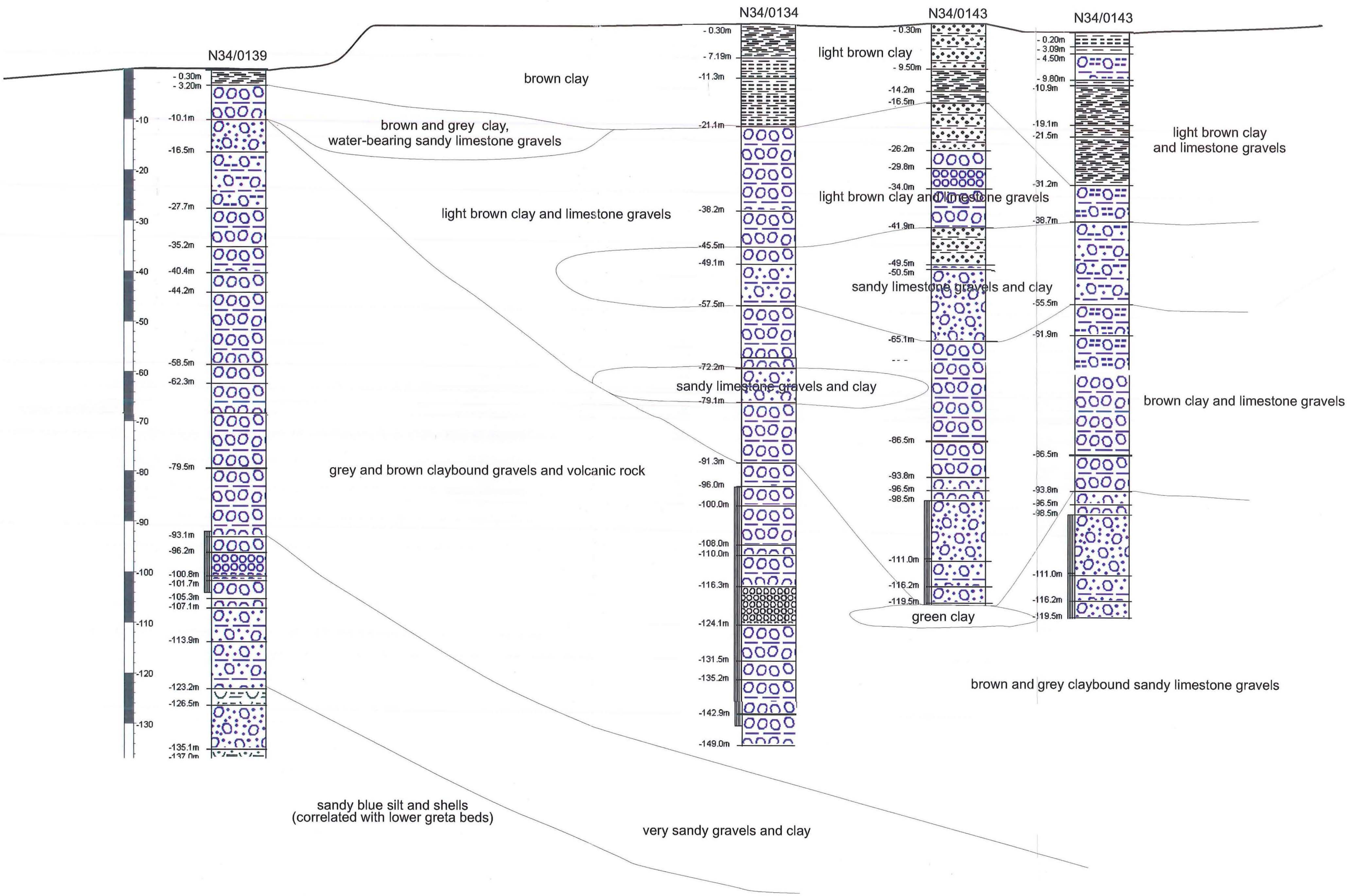
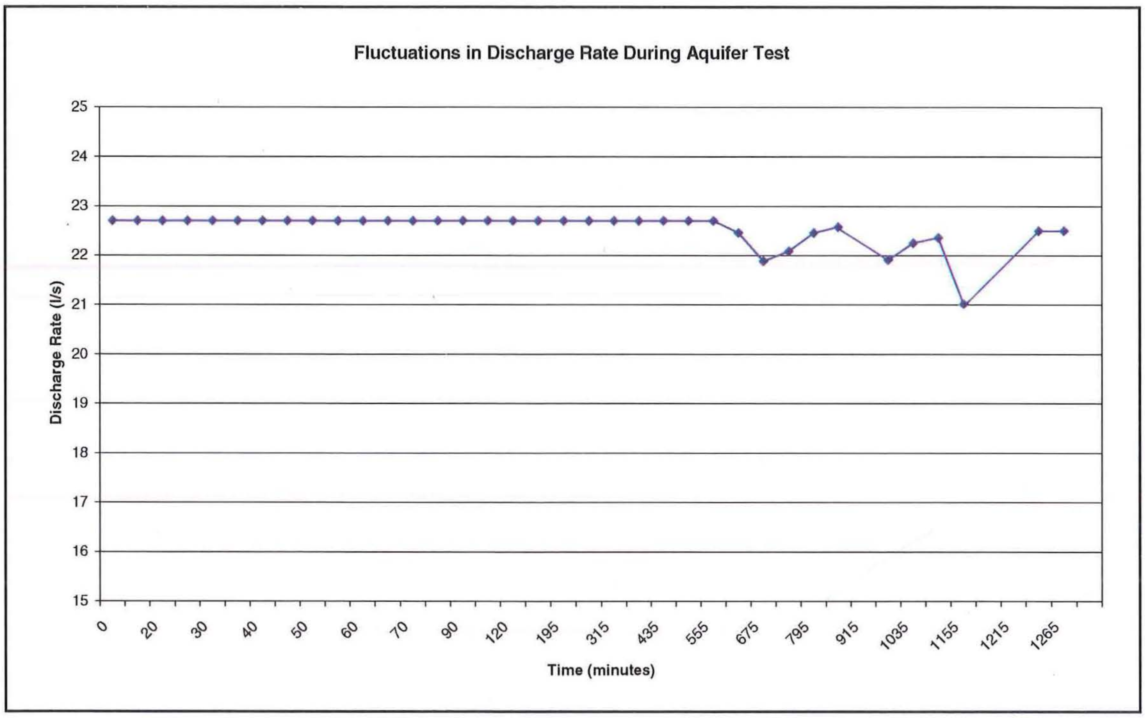


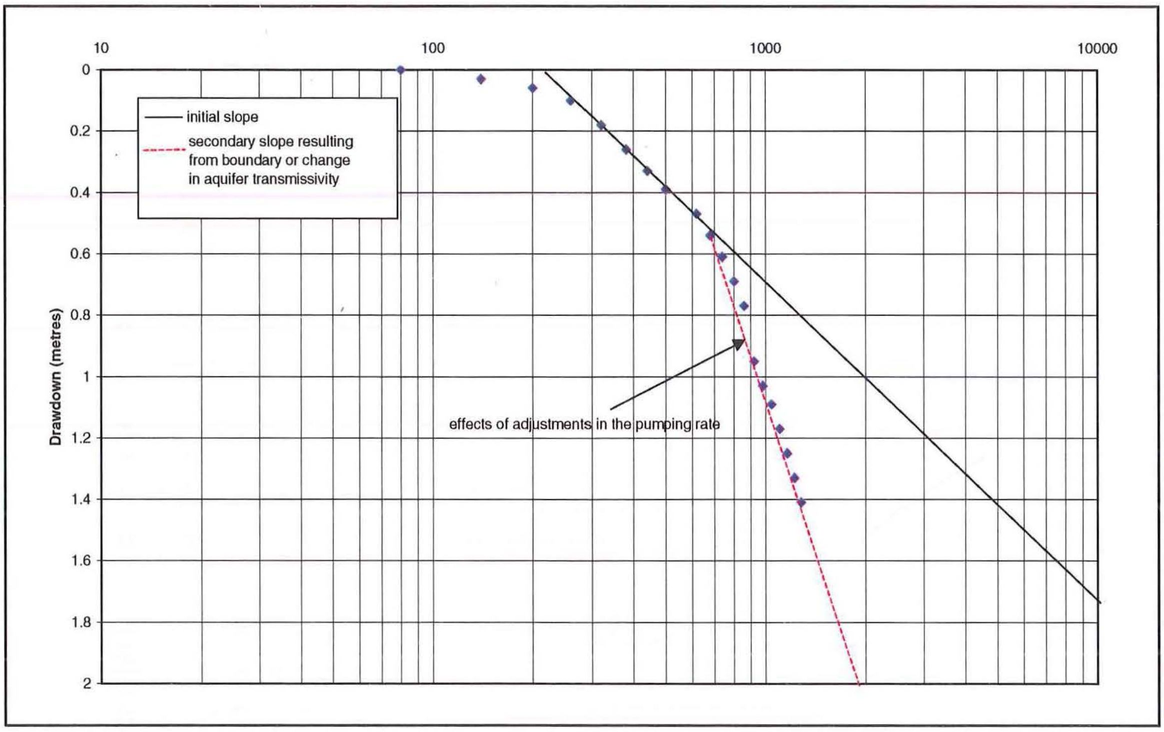
***Figure 4.22 – Discharge Rate Variability throughout the Netherwood Aquifer Test***




### 4.6.2.2 <u>Data Analysis</u>

Aquifer test field records, well logs, and details of analyses are included in Appendix D-6. Well N34/0143 was not affected by pumping. Figure 4.23 shows the semi-log plot of the time-drawdown data. At t = 615 minutes, the slope of the time-drawdown line steepens in slope, and has been interpreted as to be indicative of a reduction in the transmissivity of the aquifer as the cone of depression expands outward. Field notes indicate a reduction in discharge rate, and the discharge water becoming cloudy with an influx of sand, most likely caused by a collapse of a sand lens as a result of dewatering of the aquifer. The apparent offset in the late time-drawdown data is attributed to fluctuations in the discharge rate, and difficulties in maintaining the rate towards the end of the test. Evidence of a boundary condition is difficult to identify in the log-log plot. The log-log time-drawdown data does not represent an ideal Theis curve. However, the Netherwood pump test is the first aquifer test conducted in Omihi, and in the Kowai Gravels, and therefore, invaluable for comparing hydrogeological characteristics of the undifferentiated Kowai Gravel Aquifers with the results from the Georges Road and Broomfield-Amberley Aquifer tests, which tested the undifferentiated Canterbury – Teviotdale Aquifers (CTA).

***Figure 4.23–Time-Drawdown Semi-Log Plot for N34/0134 Illustrating the Effects of Boundary Conditions Associated with an Impermeable Boundary or Reduction in Aquifer Transmissivity***




## 4.6.3 Aquifer Test Results and Discussion

Analysis results for observation well N34/0134 is included in Table 4.8. Data was analysed with the Theis curve-fitting method by manual solution and AQTESOLV. Results from the AQTESOLV and the manual solution show some discrepancy between the both the calculated transmissivity and storativity. The discrepancies are a reflection of the preference of the best-fit curve. Calculated transmissivity values range from 74 $m^2$/day to 110 $m^2$/day, and the hydraulic conductivity is 4 - 6 m/day. The hydraulic conductivity was calculated using the aquifer thickness from the pumping well because the log for N34/0134 does not specify where the water-bearing units occur (except at 108 – 110 metres). The calculated hydraulic conductivity correlates with the suggested hydraulic conductivity for sandy gravels as outlined by Kruseman and de Ridder (1990). Given the heterogeneous and anisotropic nature of the aquifer system as indicated by the boundary conditions, the calculated results are believed to be realistic and representative values for the aquifer parameters.

***Table 4.8 – Summary of Results from Netherwood Aquifer Test***

| ***Well Number*** | ***Distance to Pumping Well (metres)*** | ***Maximum Drawdown (metres)*** | ***Boundary Observed (t= min)*** | ***Calculated Aquifer Parameters*** | | |
|---|---|---|---|---|---|---|
| | | | | *Transmissivity ($m^2$/day)* | ***Storativity*** | ***Hydraulic Conductivity (m/day)*** |
| **N34/0134** Theis | 728 | 1.41 | 15 | 74 - 110 | *.0002 - .0004* | 6 |

## 4.7 Interpretation of Aquifer Test Results for the Waipara Basin

Comparison of the aquifer test results from each of the pump test locations show that the aquifer transmissivity, storativity and hydraulic conductivity are extremely low when compared to other Canterbury aquifers, some of which have estimated transmissivities in the thousands (ECAN Aquifer Test Database 2000). The Netherwood aquifer transmissivity, while low compared to Christchurch and South Canterbury, is four times higher than the calculated transmissvities from the other two tests. Storativity is low for all of the aquifers, and reflects the nature of the aquifer medium (i.e. lithology and thickness), as do the low hydraulic conductivity values. The Broomfield-Amberley test and the Georges Road test indicate that the hydrogeologic conditions are much the same. The low transmissivity and hydraulic conductivity values revealed by the Georges Road and Broomfield test are expected to be representative of both the undifferentiated Teviotdale and Canterbury Aquifers, and the calculated values from the Netherwood aquifer test are assumed to be representative of the KGA. Interestingly, the

**Table 4.9 – Comparison of Aquifer Test Results for All Aquifer Tests**

| *Aquifer Test* | *Aquifer* | *Aquifer Thickness (m)* | *Average Transmissivity ($m^2$/day)* | *Avg. Storativity* | *Avg. Hydraulic Conductivity (m/day)* |
|---|---|---|---|---|---|
| Georges Road | CTA | 4 | 18 | .0005 | 4 |
| Broomfield - Amberley | CTA | 6 | 17 | .0001 | 3 |
| Netherwood | KGA | 19[1] | 92 | .0003 | 5 |

[1]Aquifer thickness value includes both upper and lower aquifers

values from all three tests produce similar hydraulic conductivity values which suggests that the higher calculated transmissivity of the KGA is more a function of aquifer thickness than permeability. However, the higher proportion of sand than clay and silt in the KGA than in the CTA suggests that is the combined affect of aquifer thickness and lithology.

Qualitatively, the three tests produced similar results. Data from two of the three sites indicated the presence of a boundary condition, represented by either the lateral limit of the aquifer or a decrease in aquifer transmissivity such that the drawdown responds as if the cone of depression intersected a low permeable boundary. Tests in which several observation bores were monitored, and parameters calculated, reflect the anisotropy and heterogeneity of the aquifer system, advocating the need for more pump tests to be conducted in order to evaluate the regional variations further. In addition, pump tests are invaluable for evaluating adverse effects from pumping between neighbouring wells, which cannot be determined from the well logs alone given the geologic variability.

## *4.8 Groundwater Springs*

### 4.8.1 Springs: Identification and Classification

Springs discharge in various localities throughout the valley as depression, contact, artesian, fracture and sinkhole springs (Figure 4.24). They provide an important water resource for many residents of the basin for domestic, stock and/or irrigation purposes. It is estimated that residents use a maximum of 100,000[1] cubic metres of spring water each year for irrigation, domestic, and stock supply.

Because springs are groundwaters that discharge at the ground surface, a springs survey was carried to evaluate the hydrogeologic connection between the springs and groundwater. Prior to this study only three springs had been identified and entered into the ECAN Springs Database. Classification of springs involves identification of the spring type (depression, contact, artesian, fault, fracture-joint or sinkhole), spring morphology (seepage, point source, linear/channel or horizon), discharge quantity, discharge variability, and geology. Classification and illustrations of spring types are included in Appendix D-7.

Table 4.10 provides an outline of identified spring types and associated morphologies that have been mapped in the basin. The most common type of spring occurring within the basin are depression and contact springs that discharge over a wide seepage area, and most are heavily influenced by seasonal rainfall, however, there are several that flow throughout the year. Figure 4.24 a, b, c and d are photographs illustrating the types of springs occurring throughout the region.

[1] Figure is based on personal communication with residents

Figure 4.24 - Distribution of Springs Throughout the Waipara Basin.

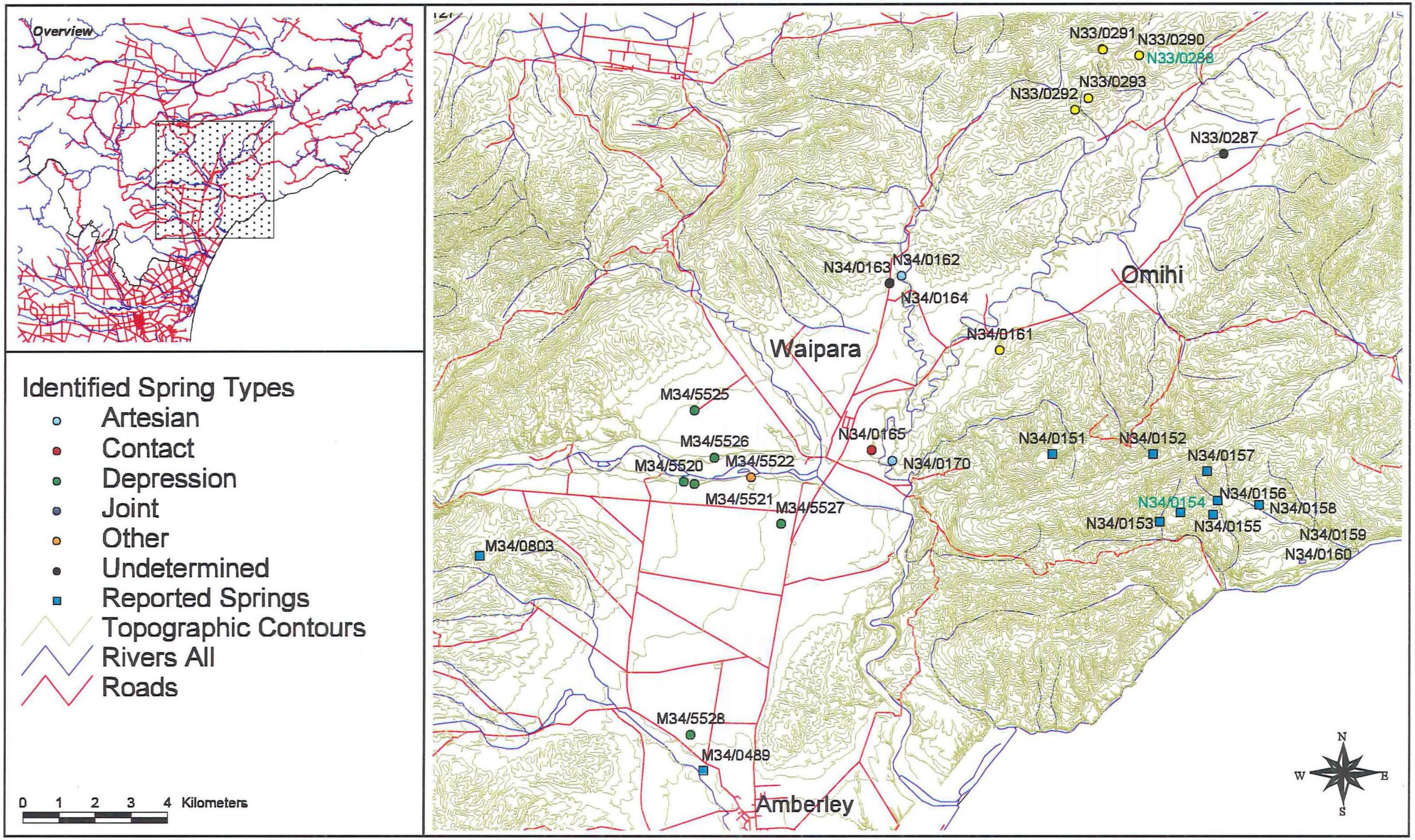


***Table 4.10 – Summary of Spring Types, Morphology and Discharge***

| Spring ID | Spring Type | Spring Morphology | Discharge Variability |
|---|---|---|---|
| M34/5520 | depression | seepage | permanent* |
| M34/5521 | depression | point source/ seepage | permanent* |
| M34/5522 | fault/contact | point source/ seepage | permanent* |
| M34/5525 | contact | seepage | intermittent |
| M34/5526 | contact | point source | permanent |
| M34/5527 | contact | seepage | intermittent |
| M34/5528 | contact | seepage | permanent |
| N34/ 0161 | joint/fracture | seepage | permanent* |
| N34/0162 | artesian | point source/ seepage | permanent |
| N34/0163 | depression | seepage | permanent* |
| N34/0164 | contact | seepage | intermittent |
| N34/0165 | contact | horizon | permanent |
| N33/0287 | depression | point source/ seepage | permanent |
| N33/0288 | joint/fracture and/or contact | seepage | permanent |
| N33/0290 | joint/fracture and/or contact | seepage | permanent |
| N33/0291 | joint/fracture and/or contact | seepage | permanent |
| N33/0292 | joint/fracture and/or contact | point source/ seepage | permanent |
| N33/0293 | joint/fracture and/or contact | point source/ seepage | permanent |

### 4.8.2 Spring Recharge to Groundwater

Springs located on the hills and ridges along the eastern and western margins of the basin are most likely flowing through fractures and joints in the Tertiary sequences, providing evidence that the Valley aquifers are being recharged from the eastern and western margins of the basin. Sinkhole springs observed on the Black anticline (Grid ref: N34: 99500-97500) testifying to the existence of karst tunnels and solution canals Many of these springs are perennial suggesting that they have long residence times. The occurrence of these springs suggests that they may be a source of recharge to the gravel aquifers, where the two are in contact. The source of the springs is most likely from local precipitation infiltrating the limestone through joints and fractures.

### 4.8.3 Spring Recharge to Surface Waters

Evidence for spring recharge to surface waters has been documented in several localities throughout the basin. N34/0170 (Figure 4.24) is an artesian spring, located at Glenray Farm in Waipara. The spring flows within the stream channel of the Omihi Stream, providing recharge to the Omihi Stream. During the summers when the Omihi Stream runs dry upstream, the spring continues to flow recharging the Omihi Stream. The exact source of the spring has not been determined at present and further fieldwork is required in order to quantify the amount of recharge to the stream.

Several springs discharge along the base of the lower terrace on the north and south side of the Waipara River as shown in Figure 4.24. The springs discharging on the south side of the Waipara River are contact springs discharging from a permeable gravel zone overlying a low permeability layer composed of silts and clays, perhaps large seepage zones. Spring discharge elevations were surveyed in to determine the potentiometric surface of the springs in relation to the Waipara River potentiometric surface. The potentiometric surface elevation of the springs is slightly higher than that of the Waipara River, and suggests that they may be hydraulically connected to the river, acting as a source of recharge. The quantity of groundwater being discharged in this area cannot be evaluated because of the seepage morphology.

***Figure 4.25- Springs of the Waipara Valley Region***

*a) Spring M34/5521 – Contact Spring located on lower terrace*

*b) Spring N34/0161 – Artesian Spring*

*c) Artesian Spring originating from joints and fractures in Tertiary sequences overlain by colluvium*

*d) N34/0165 - Contact Spring flowing from horizon along base of terrace scarp*

## 4.9 *Surface Hydrology*

The major surface water resources include the Waipara River, and its tributaries the Weka Creek, Omihi Stream, and Home Creek. Surface water resources supply a total of approximately 900,000 cubic metres per year of water to various farms throughout the valley for irrigation and commercial use. Flow gaugings of the Waipara River were completed in April 2000 in order to evaluate losses and gains to the groundwater system. Flow losses and gains for the Weka Creek, Omihi Stream, and Home Creek were evaluated from 30 years of data provided by Environment Canterbury.

### 4.9.1. Gauging Methodology

A total of six sites along the Waipara River were gauged over two days (Figure 4.26). In order to correct for the change in flow over the two-day period, one site was repeated on the second day. Gauging sites were selected where the river cross-sections were well defined, and streambeds and channels were void of vegetation, rocks and other obstacles that may affect the measured flow. Gaugings were conducted with a National Institute of Water and Atmospheric Sciences (NIWA) current metre, and a small horizontal axis Ott propeller, following the velocity-area method as outlined in the NIWA stream gauging manual (1996). Flow velocities were measured at 0.6 of the water depth. In places where the stream bottom sloped, additional readings were taken at the break in slopes. Marker pegs were installed at each gauging site, and surveyed in at a later date to determine the potentiometric surface of the river relative to sea level, and to monitor changes in river levels during the gauging period.

### 4.9.2 Waipara River Gauging Results and Interpretation

Discharge rates were calculated using the NIWA software program GAUGE version 3.2. A summary of the calculated discharge rates for each gauging site is listed in Table 4.11 and shown in Figure 4.26. Differences in measured flows greater than 10% are acceptable for the positive identification of losses and gains from the gauging data since losses and gains less than 10% fall within the acceptable margin of error. Technical difficulties prevented gaugings from being completed on one day. The Waiora site was repeated on the second day to correct for the change in flow over the two-day period.

***Figure 4.26 - Waipara River Gauging Site Locations***

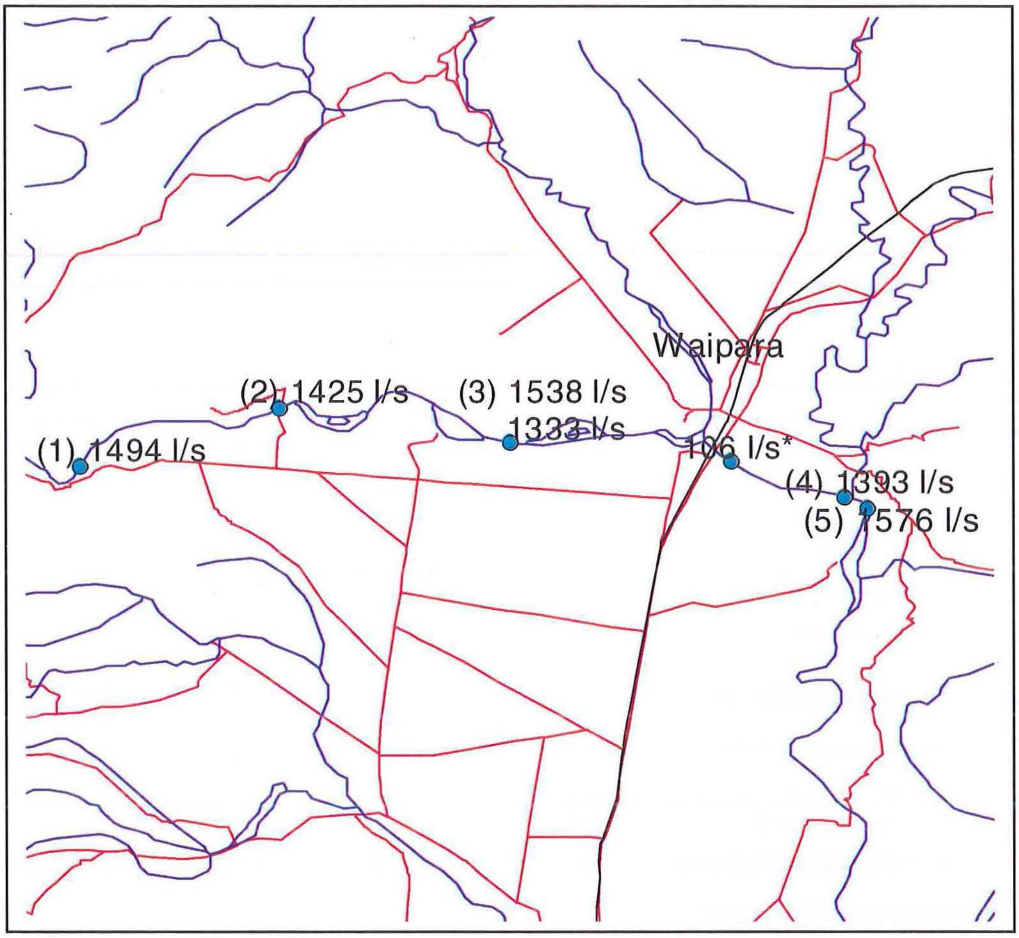



***Table 4.11 – Summary of Results from Waipara River Gaugings***

| *Site Name* | *Site Number (Figure 4.26)* | *Calculated Discharge (l/s)* | *Loss(-) / Gains (+) (l/s)* | *Loss(-) / Gains (+) (%)* |
|---|---|---|---|---|
| The Deans | 1 | 1494 | | |
| Stringers Bridge | 2 | 1425 | - 69 | -4.6 |
| Waiora | 3 | 1538 | +113 | +7.3 |
| Waiora[1] | 3 | 1333 | +93[2] | +7.0 |
| Below SH 1 Bridge | 4 | 106* | -1227 | |
| Upstream Omihi Confluence[1] | 5 | 1393 | +60 | +4.3 |
| Downstream Omihi Confluence[1] | 6 | 1576 | +183 | +11.3 |

[1]Gaugings completed on Day 2.
[2]Calculated by correcting the Stringers Road data for the decrease in flow over the two-day period
* erroneous data

There was a 4.6 % increase in flow between The Deans and the Stringers Road site, which falls within the computer estimated gauging error of 6.1%, and therefore the data is inconclusive. The Deans site is not included in the ECAN gauging program, and therefore comparisons with historical data could not be made. Between Stringers Road and Waiora (day one), the flow discharge increased by 7.3% (113 l/s). Measured flows at the Waiora site decrease by 13% (205 l/s) over the two-day period. Correcting the Stringers Road gauging data for the 13% loss results in a tabulated gain of 7% (93 l/s) between the two sites, and is in good agreement with the calculated percentage loss from the first day's data.

The calculated flow from the State Highway 1 bridge site were extremely low and is believed to be erroneous. Evaluation of the ECAN gauging database indicates that the data is anomalous as there are no recorded losses of the same magnitude. ECAN gauging data shows minimal gains occur between these two sites, most of which are observed during the winter months, and has been attributed to gains from the Weka Creek that flows during a portion of the winter season. A comparison of the calculated flows for Waiora and upstream of the Omihi Stream confluence indicates that shows an increase of 4.3% (60 l/s). The discharge increases by 11.6% (183 l/s) downstream of the Omihi confluence, and is attributable to contributions from the Omihi Stream. Given the estimated error percentage and the small magnitude of calculated increases and decreases in discharge for most of the gauged sites (excluding the gauging site downstream of the Omihi confluence), the data suggests that minimal interaction between the groundwater and Waipara River are occurring, and that the Waipara River between The Deans and downstream of the Omihi Confluence is predominantly a gaining river.

### 4.9.3 ECAN Gauging Data and Interpretation

Gauging data for the Weka Creek, Omihi Stream, and Home Creek was supplied by the ECAN Environmental Monitoring Surface Hydrology Section. The Gauging records were used to evaluate surface-groundwater interactions. Records show that there is not a single day in which all sites along the Omihi and Home Creeks were gauged. Presented gauging data represents dates in which the maximum number of sites were gauged on a single day. Weka Creek gauging data are inadequate for evaluating stream losses and gains because no gaugings were carried out along the entire length of the stream on one single day. All ECAN gauging data presented is included in Appendix D-9.

A summary of the collated data is included in Figure 4.27 and calculated losses and gains are listed in Table 4.12. Examination of the data shows that there is only one site that shows a decrease in discharge. Data from the Home Creek site no.3 shows a loss of 7 l/s (11.8%) between Kings Road and the Stratford's. Based on available data, the maximum gain from the groundwater system occurs between Glenmark Bridge and Kings Road.

The Omihi does not appear to lose or gain any groundwater between Baxter's Bridge (site 5) and No. SH1 (site 6), however, there have been only two recorded gaugings at this site, only one of which was completed at the same time as the other sites along the stream. Significant gains appear to occur throughout the length of its course, however, because there is not a single date in which all sites were gauged, it is difficult to assess the total gain from groundwater for the length of the stream. Calculations show that there is a gain of 99 l/s between Baxter's Bridge (1) and downstream of the Home Creek Confluence (7), of which 81 % is attributed to the confluence of Home Creek, and 19 % is attributable to gains from the groundwater system. For sites downstream of the Home Creek confluence, the differentiation between gains from groundwater versus surface water inputs becomes more complex as all sites were not gauged on a single day. For example, a gain was recorded in the 1973 gaugings between the No. SH 1(6) and the Waipara Township site (8), however, because there is no data for the Home Creek Confluence site (7), it is difficult to assess what percentage of the total gain is from groundwater. The same applies for the 1973 gaugings between the Waipara Township site (8) and the Waipara Confluence site (10) in which no gauging was carried out for the Washcreek Farm site (9). In addition, the October 21 1987 gauging recorded an increase in discharge between the Home Creek Confluence site (7) and the Washcreek Farm site (9), and no gaugings were carried out for the Waipara Township site (8).

**Figure 4.27 - ECAN Gauging Data for Selected Sites**

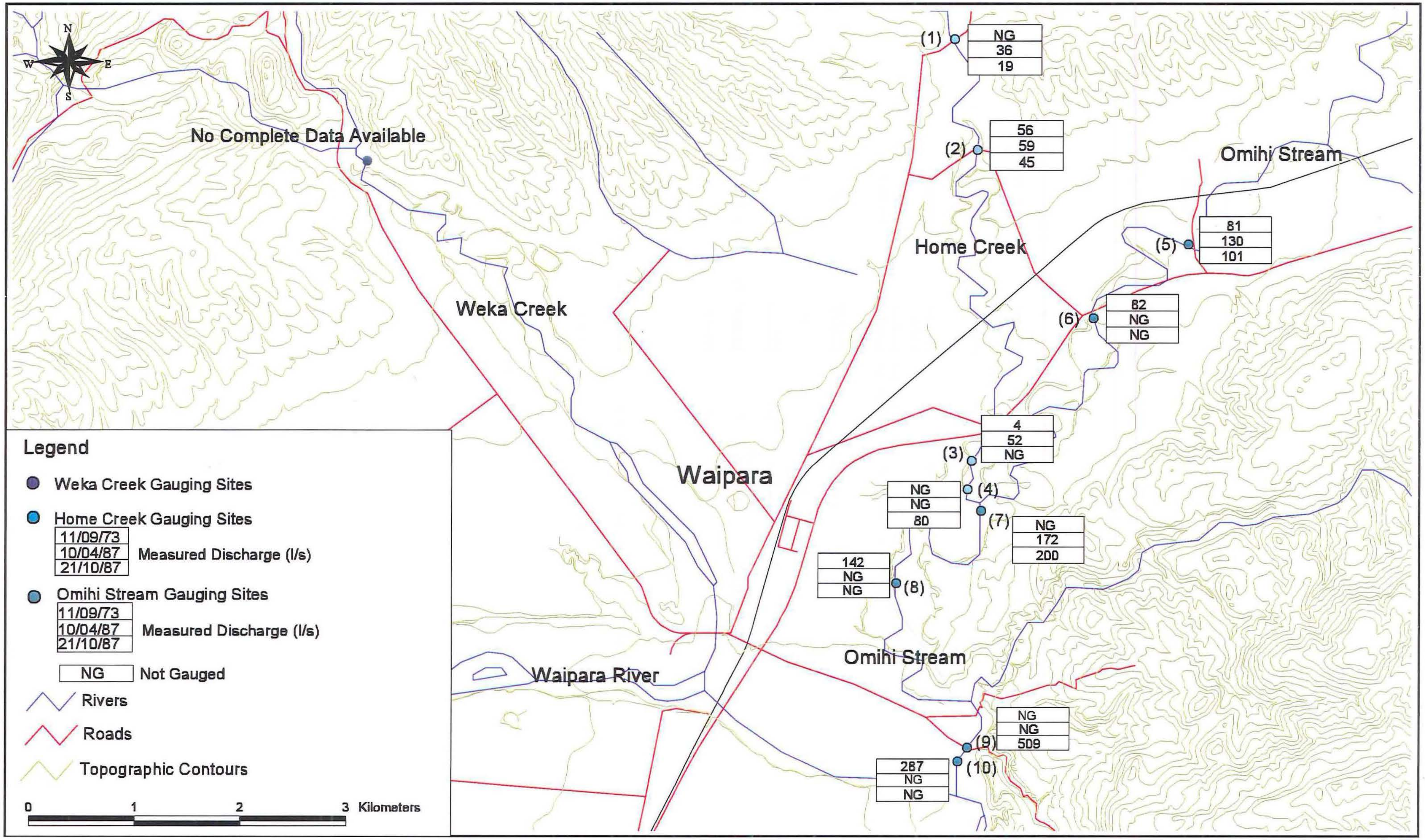


*Table 4.12 – Selected ECAN Gauging Data for Home Creek and Omihi Stream*

| No.[1] | ECAN Gauging Site | Measured Discharge (l/s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 11/09/1973 | | | 10/04/1987 | | | 21/10/1987 | | |
| | **Home Creek** | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) |
| 1 | Glenmark Bridge | | | | 36 | | | 19 | | |
| 2 | Kings Road | 56 | +11 | 55.0 | 59 | +23 | 40.0 | 45 | +26 | 57.8 |
| 3 | Stratford's | 4 | -16 | 20.0 | 52 | -7 | 11.8 | | | |
| 4 | US Omihi Confluence | | | | | | | 80 | +35 | 43.8 |
| | | 11/09/1973 | | | 10/04/1987 | | | 21/10/1987 | | |
| | **Omihi Stream** | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) | Flow (l/s) | Loss/Gain (l/s) | Loss /Gain (%) |
| 5 | Baxter's Bridge | 81 | | | 130 | | | 101 | | |
| 6 | No. SH1 | 82 | +1 | 1.2 | | | | | | |
| 7 | DS Home Creek Confluence | | | | 172 | +42 | 24.4 | 200 | +99 | 49.5 |
| 8 | Waipara Township | 142 | +60 | 42.3 | | | | | | |
| 9 | Washcreek Farm | | | | | | | 509 | +309 | 60.7 |
| 10 | Waipara Confluence | 287 | +145 | 50.5 | | | | | | |

Despite the lack of gauging data, the overall conclusion from the existing data shows that the Home Creek and Omihi Stream are gaining streams and are not contributing any measurable amounts of recharge to the groundwater system.

## 4.10 Groundwater Fluctuations

Approximately 45 wells have been monitored bi-monthly since June 1999. The main objective of the water level monitoring programme was to evaluate the seasonal groundwater fluctuations and associated recharge events. Monitoring wells were chosen based on accessibility, usage and location.

Long-term fluctuations occur as a result of annual climatic effects associated with extended periods of high rainfall or drought. In addition, increases in groundwater abstraction rates and usage can result in a lowering of regional groundwater levels if the amount of groundwater abstraction exceeds the natural rate of recharge. Long-term fluctuations have not been assessed since extensive monitoring of water levels has just begun. Previous records of long-term water level monitoring data for Waipara wells are minimal and periodic. In addition, many of the records are for the shallow, disused brick wells or for wells that have either been filled in or cannot be located.

Observed short-term fluctuations water levels are most likely caused by to changes in atmospheric pressure, rainfall infiltration, and external loading of the unsaturated zone resulting in an increase in pressure in the confined aquifers during periods of high rainfall, and pumping effects. Selected groundwater level plots are included in Appendix D-10.

### 4.10.1 Regional Trends

Based on data collected during this study, monitored groundwater levels for Omihi south to Broomfield-Amberley show a gradual rise in water levels from August to October coinciding with the spring recharge. Water levels reach a maximum in October and November after which water levels decline steadily over the summer months coinciding with periods of low rainfall. Water levels begin to recover in late March and April corresponding to periods of increase rainfall during the autumn months.

Shallow aquifers (< 15 metre) show the greatest fluctuations with seasons indicating that the dominant source of recharge is from surface infiltration. Many of these wells become dry during prolonged periods of low rainfall. Most of the intermediate aquifers (20 – 40 metres) show a gradual decline in water level, but respond relatively quickly to Spring and autumn recharge events. The observed response is the result of infiltration of precipitation where the aquifer is unconfined, which increases the hydraulic pressure in the confined portion of the aquifer causing the potentiometric surface to rise. All wells monitored are penetrating confined aquifers and therefore, daily responses to rainfall were not observed.

Almost all the hydrographs show a marked decrease from February to March/April and is attributed to the combined effect of an increase in groundwater abstractions during the irrigation season, and a decrease in rainfall recharge during the summer months. Wells in which pumping effects were not observed are either new wells that have not been utilised yet, are remote and too far away from other wells to be affected by groundwater abstractions, or are old wells disused wells with degraded hydraulic connection (i.e. silted up, clogged screen).

### 4.10.2 Regional Variations

Groundwater fluctuations for wells located in Omihi and Broomfield-Amberley showed similar seasonal responses, however, observed water levels in well N34/0049 (34.0 m), N34/0060 (33.5 m) and M34/0722 (66.0 m) showed anomalous fluctuations. Hydrographs show recharge events occurring from November through December, and additional recharge events in May through June. The summer recharge event does not correspond to the overall regional recharge trends observed in other wells, and therefore may represent a delayed response to spring recharge associated with an increase in precipitation. The late response is best explained by a slower rate of infiltration and groundwater flow compared to other monitored areas.

### 4.10.3 Response to Stream Flow

Based on the findings of the previous section, it has been shown that the surface waters of the Waipara Basin do not providing significant recharge to the groundwater system, and therefore, fluctuations in measured well water levels are not related to fluctuations in stream flow, except for shallow wells located along the modern day floodplains of rivers and streams. It is expected that these wells are hydraulically connected to the underflow of the surface waters, and observable fluctuations are related to the variations in stream flow. No wells located along the modern day floodplains have been monitored during this study. Comparison of water level fluctuations for selected shallow wells (< 20 meters) located on the main Canterbury surface (M34/0043, M34/0041 and M34/0678) with river discharge data recorded at White Gorge Gauging Station shows that the fluctuations in water levels are independent of the river stage levels. Data plots are included in Appendix D-10.

Assessment of the effects of stream flow on groundwater fluctuations for the wells located in the Glenmark and Omihi areas could not be carried out because there are no stream flow recorders on the Weka Creek, Home Creek and Omihi Stream.

### 4.10.4 Response to Barometric Pressure

All monitored wells penetrate confined aquifers, and therefore, are expected to correlate well to barometric pressure fluctuations. Comparison of water levels for three wells of different depth (M34/0043-10 m, M34/0743 – 29.7 m and M34/0364 – 74.0 m) with barometric pressure data from Christchurch Airport shows that water levels in the shallower wells do not correlate well with barometric pressure. However, water levels for M34/0364 respond well showing a rise in water level with a decreasing barometric pressure and vice versa. This response is not observable in unconfined conditions and therefore, suggests that the other aquifers penetrated by M34/0043 and M34/0691 are confined over an extensive area.

## *4.11 Chapter Summary*

Groundwater resources are found within the waipara and omihi gravels (Canterbury Gravels), the Teviotdale and the Kowai Gravels. The aquifers found within the omihi and waipara gravels cannot be distinguished from the aquifers occurring within the Teviotdale Gravels because their hydrogeological properties are similar. Aquifers occurring within the KGA appear to be more transmissive based on reported yields and the Netherwood aquifer test, however, comparison of the average hydraulic conductivity values listed in Table 4.13 shows the tested aquifers to be within the same range. Because the aquifers exhibit variable thicknesses, the hydraulic conductivity values are a better reflection of the hydrogeologic properties of the tested aquifers. Although the yields of the deeper KGA are higher, wells screens extend for several metres of individual water-bearing units in order to maximise the yield potential of the well.

**Table 4.13 – Comparison of Aquifer Test Results for All Aquifer Tests**

| **Aquifer Test** | **Aquifer** | ***Aquifer Thickness (m)*** | **Average Transmissivity ($m^2$/day)** | **Average Storativity** | **Avg. Hydraulic Conductivity (m/day)** |
|---|---|---|---|---|---|
| Georges Road | CTA | 4 | 18 | .0005 | 4 |
| Broomfield - Amberley | CTA | 6 | 17 | .0001 | 3 |
| Netherwood | KGA | 19[1] | 92 | .0003 | 5 |

[1]Aquifer thickness value includes both upper and lower aquifers

Figure 4.28 (pocket) presents a schematic illustration of the spatial relationship between hydrogeologic features of the Waipara alluvial basin. The figure shows 11 wells penetrating the KGA and CTA hydrogeologic units. Wells MW 1 and MW 3 are drilled to different depths but penetrate the same aquifer in the Kowai Gravels because of uplift and folding during and after deposition. The aquifer lithologies, yields and hydraulic properties will be similar, although the aquifer thicknesses will be different. The measured potentiometric surfaces of these two wells are equal. Conversely, MW 3 and MW 9 penetrate to the same depth, but because of folding the two wells intercept different aquifers, which exhibit different potentiometric surfaces, aquifer lithologies, hydraulic properties and thicknesses.

Wells MW 2 and MW 4 are drilled to the same depths and penetrate aquifers contained in two different hydrogeologic units. MW 2 penetrates alluvial fan deposits in which the aquifers are lower yielding. The aquifer penetrated by MW 4 is a channel deposit that has been reworked and sorted, and therefore is higher yielding. Well MW 5 and MW 9 penetrate the same KGA unit, but because MW 5 in screened in the shallower aquifer in the CTA as well, the potentiometric surface will differ from that of MW 9.

Well MW 6, MW 7, MW 10 and MW 11 all penetrate to the same depths. MW 6 is the highest yielding well of them all because it penetrates an ancestral river channel that is well sorted and more permeable. The hydrogeological properties exhibited by MW 6 are completely different, and therefore cannot be correlated with other wells. Well N34/0131 located in Glenmark may be representative of such a well. The well is 76.6 metres deep and has a yield of 18 l/s. The aquifer is only 2 metres thick, and therefore must be extremely permeable and confined over an extensive area as the water level rises to approximately 22 metres above ground level. Well MW 7 and 11 exhibit similar hydrogeological properties as they penetrate the same hydrogeological unit, which is low yielding, poorly sorted CTA layer. MW 10 and MW 11, however, penetrate different aquifers, which exhibit different hydrogeological properties although they are in close proximity to one another. The KGA penetrated by MW 10 is higher yielding and exhibits different hydrogeological properties to MW11. Because of the fault-propagated fold, these aquifers may be recharged from a different source than the other aquifers on the downthrown side of the fault.

Several types of springs are illustrated. Joint and fracture springs (left) are shown discharging from the faulted and uplifted Torlesse and Tertiary rocks, which are in contact with the Canterbury Gravel alluvial fan surface. Because the alluvial fan surface is poorly sorted and relatively impermeable, the springs flow over the alluvial surface. Contact springs (centre) discharge along terrace scarps where groundwater seeps from buried water-bearing channels as shown in Figure 2.3 and 4.25d. In addition, where faults have displaced the gravel aquifers against relatively impermeable deposits, contact springs will discharge along the surface, forming swampy areas and seepage zones as documented in previous sections. In some places, permeable zones may provide conduits for recharging the surface waters (centre).

The depositional and structural environment of the basin controlled the spatial distribution, and the hydrogeologic relationship between the CTA and KGA. The model presented provides an interpretation for the observed physical and hydraulic properties of the hydrogeology of the Waipara alluvial basin, as documented by samples of drill cuttings, sediment analyses, constructed cross-sections, potentiometric data, aquifer tests, and the spring and surface water investigations.

# CHAPTER FIVE: GROUNDWATER CHEMISTRY

## *5.1 Introduction*

Chemical sampling and analyses of selected wells, springs, and surface waters were carried out to determine the chemical characteristics of the groundwater resources, to identify formation specific chemical signatures, and to identify broad regional differences in water chemistry in order to better define hydrogeologic regimes and sources of recharge.

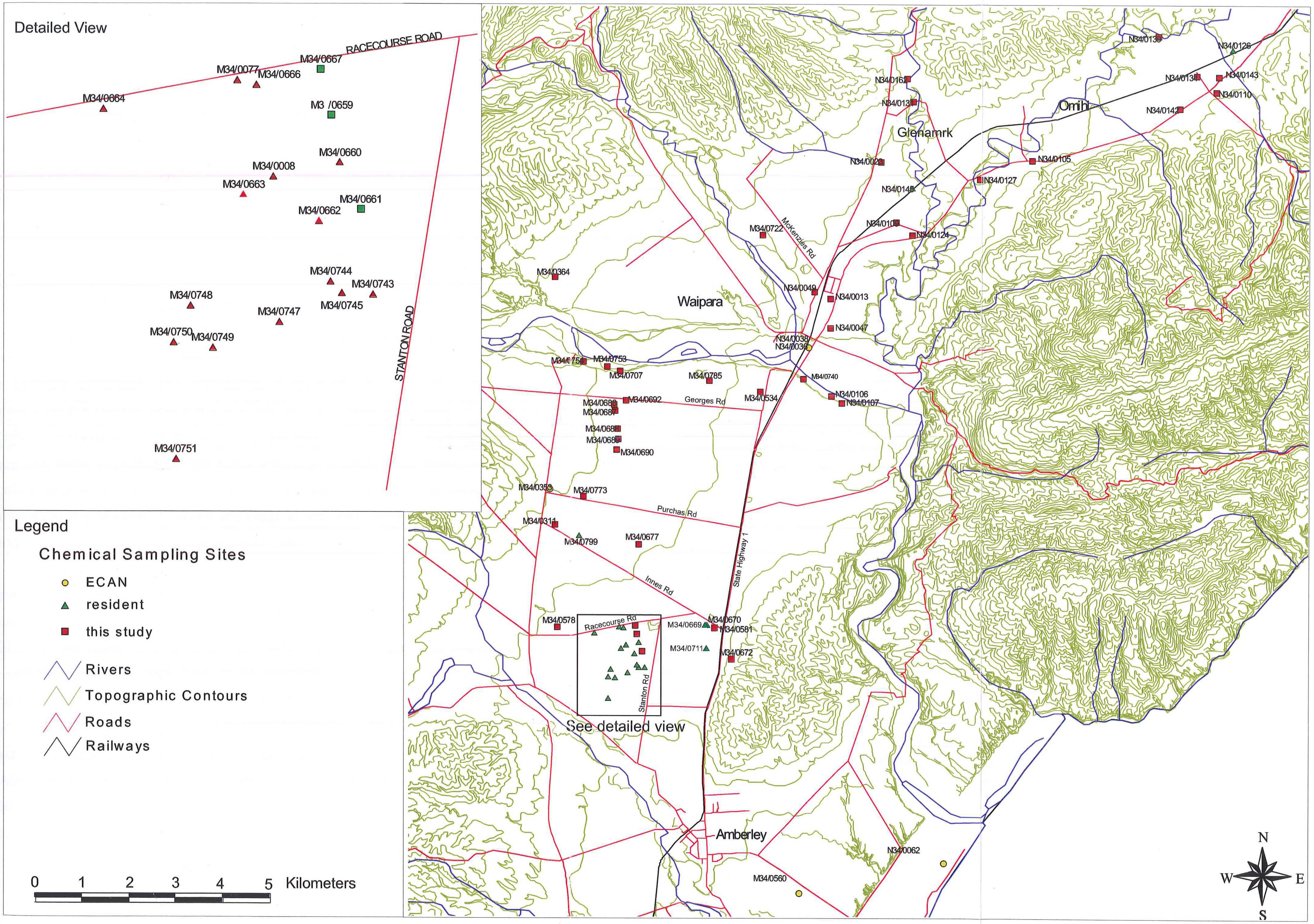
Prior to this study, Environment Canterbury (ECAN) obtained chemical data for four wells located within the study area (M34/0311, M34/0353, N34/0036, and M34/0038) as shown in Figure 5.1. Well M34/0353 has been monitored by the ECAN Water Quality section since 1995. ECAN samples for wells N34/0036, N34/0038 and M34/0311 were analysed to test the potability of the water. Parameters analysed were limited to pH, alkalinity, conductivity, calcium, iron, manganese, sulphate, nitrogen species suite, chloride, coliforms, and total hardness, and therefore, the data could not be used for groundwater classification as groundwater classification studies require the analysis of all the major cations and anions ($Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $K^+$, $HCO_3^-$, $CO_3^-$, $SO_4^-$, $NO_3^-N$). Other data presented includes chemical data provided by residents who had their wells tested during the development of the well. Unfortunately, the use of the data is limited as the chemical parameters analysed for were for water potablility and irrigation rather than aquifer characteristics. In addition, analytical results provided by residents were from samples collected at different times, spanning a period of several years which makes it difficult to identify true differences in the groundwaters. Chemical analyses provided by residents were used for identifying regional and local trends, and for designing a chemical sampling programme.

## *5.2 Chemical Sampling Programme*

### 5.2.1 Sampling and Analytical Methods

A total of 40 samples were collected from 38 wells. Figure 5.1 shows the well locations

*Figure 5.1 - Chemical Sampling Locations, Water Chemistry Data supplied by Residents and ECAN Monitoring Sites*



of samples collected during this study, sites from which data was provided by the residents, and the ECAN water quality monitoring sites. Of the thirty-eight groundwater samples, two samples were duplicate samples collected during pump tests to compare groundwater chemistry at the start and end of the test. Sample sites were selected on the basis of location, well depth, well log data, and accessibility. Additional samples include spring N34/0162 (Gould) and Home Creek. Shirley Hayward of the ECAN Environmental Quality section provided the chemical sampling analyses for the Waipara River.

#### *5.2.1.1* Sampling Methods

The majority of wells were sampled by using the installed pumps to purge the water from the casing and the aquifer. Wells that did not have pumps installed were sampled by using a portable Grunfos submersible mini-pump, capable of pumping up to 0.5 l/s on a portable generator. The mini-pump is lowered into the well and positioned approximately 0.5 metres above the well screen. For open-pipe wells, the pump was positioned 0.5 metres above the bottom of the well. The pump is then secured at the surface, and water is pumped to the surface through a teflon hose. Wells were sampled after three volumes of water were purged from the well. Purging times were determined by calculating the volume of water enclosed in the well, multiplying it by three, and dividing the resultant volume by the pumping rate.

Samples were taken directly off the well where possible to minimise the risk of contamination occurring from the service line or storage tanks. For wells pumped with the Grunfos mini-pump, the samples were taken from the teflon hose discharge point. The sampling methods and procedures followed were based on the procedures outlined in an unpublished Canterbury Regional Council report, *Surface Water Quality, Groundwater Quality, Biological and Habitat Assessment: Field and Office Procedures Manual* (CRC Report, 1998). In addition, practical training for sampling was undertaken with Mark Robertson of the ECAN Environmental section. Field measurements of pH, alkalinity, conductivity and dissolved oxygen were made with field equipment when equipment was working and available.

#### 5.2.1.2 Analytical Methods

Samples were analysed for the purpose of evaluating the chemical signatures of aquifers. Measured chemical parameters include pH, alkalinity, conductivity, total hardness, in addition to the major cations and anions, which include sodium ($Na^{+}$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), iron ($Fe^{++}$), potassium ($K^{+}$), bicarbonate ($HCO_3^-$), carbonate ($CO_3^-$), sulphate ($SO_4^-$), and nitrate nitrogen ($NO_3^-$-N). Analysis of minor chemical constituents included bromide ($Br^-$), manganese ($Mn^{2+}$), and reactive silica. Thirty-four samples underwent a comprehensive analysis, and the four remaining samples were analysed for pH, conductivity and alkalinity. Only 21 samples were analysed for bromide, as funding was limited. All samples were analysed at the Environment Canterbury Laboratory in Christchurch, and Appendix E-1 includes a summary of the parameters analysed by the ECAN laboratory with the analytical method of measurement, detection limits and the cost of each method.

## 5.3 Groundwater Chemistry Results

### 5.3.1 Groundwater Quality and Regional Trends

A summary of the results from the chemical sampling programme is presented in Table 5.1. Twenty-six samples transgressed the 1995 Drinking-Water Standards of New Zealand (DWSNZ) aesthetic based guideline value of 0.2 g/m$^3$ for iron ($Fe^{2+}$), and twenty-seven transgressed the suggested aesthetic based guideline values for manganese ($Mn^{2+}$), with one sample exceeding the DWSNZ health-based maximum acceptable value (MAV) for manganese. Samples that exceed guideline values are highlighted in Table 5.1. A table of the 1995 DWSNZ guideline values for the major chemical constituents are included in Appendix E-2.

Figures 5.2a and 5.2b show the geographic distribution of the major cation and anion concentrations (mg/l) for sampled wells, and four Waipara River samples. Overall, chemical data shows that Waipara groundwaters are enriched in calcium ($Ca^{2+}$) and sodium ($Na^{+}$) cations, as well as bicarbonate ($HCO_3^-$) and chloride ($Cl^-$) anions. Potassium ($K^{+}$), magnesium ($Mg^{2+}$) and sulphate ($SO_4^-$) are present in relatively low concentrations. Regional trends show sampled groundwaters south of the Waipara River are enriched in sodium, whereas sampled aquifers north of the Waipara River

## Table 5.1 - Summary of Waipara Chemical Data

| Well ID | M34/0105 | M34/0311 | M34/0353* | M34/0364 | M34/0534 | M34/0560 | M34/0578 | M34/0581 | M34/0659 | M34/0659 (2) | M34/0672 | M34/0677 | M34/0686 | M34/0687 | M34/0688 | M34/0689 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well Depth (m) | 114.3 | 30.0 | 39.5 | 74.0 | 42.0 | 19.5 | 66.0 | 27.8 | 28.0 | 28.0 | 35.7 | 11.8 | 34.8 | 21.8 | 27.7 | 24.8 |
| pH | 7.5 | 7.0 | 7.3 | 7.4 | 7.1 | 7 | 7.6 | 7.5 | 7.2 | 7.6 | 7.3 | 6.6 | 7.9 | 8.2 | 6.4 | 7.1 |
| Alkalinity to pH 4.5 as $HCO_3$ (mg/L) | 159 | 42 | 70 | 300 | 76 | 130 | 140 | 160 | 57 | 96 | 190 | 27 | 74 | 87 | 24 | 59 |
| Alkalinity to pH 8.3 as $CO_3$ (mg/L) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bromide (mg/L) | 0 | 0.071 | nm | 0.56 | NM | 0.094 | 0.052 | 0.072 | NM | NM | 0.22 | nm | 0.07 | 0.06 | nm | nm |
| Calcium (mg/L) | 24 | 14 | 21 | 110 | 9.6 | 28 | 18 | 29 | 11 | 16 | 40 | 11 | 18 | 17 | 17 | 11 |
| Chloride (mg/L) | 42 | 15 | 14 | 140 | 14 | 33 | 14 | 33 | 13 | 11 | 15 | 18 | 23 | Contaminated Sample [illegible]4 | 13 | 14 |
| Conductivity at 25 C (mS/m) | 0 | 18 | 22 | 96 | 16 | 31 | 27 | 38 | 17 | 20 | 58 | 22 | 23 | [illegible]1 | 25 | 17 |
| Iron (mg/L) | 0.2 | 0.47 | 0.12 | 0.2 | 0.2 | 0.21 | 0.73 | 0.25 | 0.73 | 1.9 | 0.71 | <0.12 | 0.53 | 8.5 | 0.31 | <0.12 |
| Magnesium (mg/L) | 7 | 2.0 | 3.5 | 13 | 3.5 | 4.8 | 8.7 | 9.6 | 3.5 | 3.9 | 13 | 4.7 | 3.9 | 4.5 | 4.6 | 4.3 |
| Manganese (mg/L) | <0.04 | 0.21 | 0.04 | 0.07 | 0.087 | 0.47 | 0.22 | 0.28 | 0.07 | 0.12 | 0.43 | <0.04 | 0.08 | 0.[illegible]4 | 0.05 | 0.23 |
| Nitrate Nitrogen (mg/L) | <0.025 | 7.9 | 6 | 2.9 | <0.025 | <0.025 | <0.025 | 0.2 | 2.3 | 0.5 | 0.7 | 12.9 | 6.0 | [illegible]4 | 17.0 | 3.0 |
| Potassium (mg/L) | 1.8 | 1.1 | 1.2 | 1.5 | 0.81 | 1.1 | 1.3 | 1.5 | 1.2 | 2.3 | 1.7 | 2.1 | 1.2 | 2.7 | 2.1 | 1 |
| Reactive Silica (mg SiO2/L) | 20 | 26 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 14 | 20 | 20 | 14 | 11 | 22 | 19 |
| Sodium | 81 | 15 | 18 | 46 | 20 | 30 | 26 | 27 | 18 | 22 | 49 | 21 | 21 | 23 | 25 | 16 |
| Sulphate (mg/L) | 11 | 1.6 | 6.1 | 14 | 3.6 | 3.6 | 4.7 | 7.3 | 3.9 | 3.5 | 19 | 7.5 | 5.1 | 8.8 | 8.3 | 2.6 |
| Total Hardness (mg $CaCO_3$/L) | 155 | 43 | 67 | 328 | 38 | nm | 81 | 112 | 42 | 56 | 153 | 47 | 61 | 61 | 49 | 45 |
| Total Dissolved Solids (TDS)** | 346 | 143 | 166 | 723 | 68 | 265 | 228 | 296 | 106 | 174 | 388 | 88 | 168 | 178 | 137 | 122 |

| Well ID | M34/0689 (2) | M34/0690 | M34/0692 | M34/0707 | M34/0722 | M34/0754 | M34/0773 | M34/0785 | N34/0013 | N34/0023 | N34/0047 | N34/0049 | N34/0062* | N34/0105 | N34/0106 | N34/0107 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well Depth (m) | 24.8 | 26.2 | 27.8 | 33.4 | 66.0 | 42.0 | 26.0 | 27.7 | 27.7 | 26.0 | 27.0 | 34.4 | 75.0 | 25.3m | 68.0 | 28.0 |
| pH | 7.0 | 7.3 | 7.6 | 8.0 | 7.7 | 7.7 | 6.9 | 7.2 | 7.7 | 7.0 | 7.4 | 7.3 | 7.5 | 7.1 | 7.7 | 7.9 |
| Alkalinity to pH 4.5 as $HCO_3$ (mg/L) | 55 | 66 | 64 | 130 | 200 | 140 | 42 | 52 | 170 | 99 | 180 | 160 | 180 | 470 | 140 | 103 |
| Alkalinity to pH 8.3 as $CO_3$ (mg/L) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bromide (mg/L) | nm | 0.08 | nm | nm | nm | nm | 0.06 | 0.08 | 0.10 | 0.31 | nm | nm | 0.25 | 1.2 | 0.05 | nm |
| Calcium (mg/L) | 11 | 15 | 17 | 36 | 57 | 29 | 15 | 17 | 48 | 17 | 45 | 49 | 64 | 220 | 23 | 12 |
| Chloride (mg/L) | 15 | 15 | 13 | 22 | 22 | 12 | 20 | 15 | 23 | 54 | 20 | 25 | 67 | 300 | 12 | 12 |
| Conductivity at 25 C (mS/m) | 18 | 20 | 20 | 30 | 47 | 28 | 22 | 21 | 42 | 42 | 41 | 42 | 54 | 180 | 27 | 20 |
| Iron (mg/L) | 0.12 | 0.44 | 1.3 | <0.12 | <0.12 | 0.26 | 0.37 | 0.21 | 1.3 | 1.7 | 3.7 | <0.12 | <0.12 | 3.5 | 0.22 | 0.38 |
| Magnesium (mg/L) | 4.3 | 3.7 | 2.7 | 3.6 | 7.5 | 4.4 | 4.7 | 4.2 | 6.2 | 5.4 | 7.2 | 5.4 | 7.9 | 14 | 6.4 | 4.0 |
| Manganese (mg/L) | 0.24 | 0.30 | 0.10 | <0.04 | <0.04 | <0.04 | 0.29 | 0.06 | 0.07 | 0.15 | 0.04 | <0.04 | <0.04 | 0.98 | 0.05 | 0.07 |
| Nitrate Nitrogen (mg/L) | 4.0 | 4.8 | 5.2 | 1.2 | 0.7 | 0.4 | 11 | 8.3 | 0.7 | 4.2 | 2.2 | 1.1 | 0.18 | <0.025 | <0.025 | <0.025 |
| Potassium (mg/L) | 1.2 | 1.2 | 1.3 | 1.3 | 2.8 | 1.3 | 1.2 | 1.1 | 1.8 | 0.77 | 2.9 | 2.3 | 2.3 | 2.2 | 1.2 | 1.0 |
| Reactive Silica (mg SiO2/L) | 19 | 21 | 15 | 18 | 15 | 19 | 22 | 22 | 19 | 27 | 13 | 18 | 20 | 31 | 20 | 7.4 |
| Sodium | 16 | 16 | 17 | 20 | 25 | 19 | 16 | 15 | 24 | 54 | 22 | 23 | 37 | 110 | 25 | 23 |
| Sulphate (mg/L) | 2.6 | 2.5 | 3.9 | 12 | 38 | 4.9 | 1.9 | 2.9 | 38 | 16 | 33 | 4.2 | 12 | 91 | 4.6 | 3.1 |
| Total Hardness (mg $CaCO_3$/L) | 45 | 53 | 54 | 277 | 173 | 91 | 57 | 60 | 145 | 65 | 142 | 145 | 192 | 607 | 84 | 46 |
| Total Dissolved Solids (TDS) | 129 | 148 | 141 | 254 | 385 | 211 | 129 | 137 | 353 | 280 | 329 | 288 | 391 | 1244 | 233 | 166 |

| Well ID | N34/0109 | N34/0110 | N34/0124 | N34/0127 | N34/0131 | N34/0134 | N34/0139 | N34/0142 | N34/0162 |
|---|---|---|---|---|---|---|---|---|---|
| Well Depth (m) | 23.3 | 48.0 | 28.0 | 24.0 | 76.6 | 145.0 | 137.0 | 155.0 | spring |
| pH | 7.5 | 7.1 | 7.3 | 7.5 | 7.8 | 7.0 | 7.9 | 7.4 | 7.6 |
| Alkalinity to pH 4.5 as HCO3 (mg/L) | 230 | 450 | 230 | 320 | 210 | 320 | 210 | 330 | 260 |
| Alkalinity to pH 8.3 as CO3 (mg/L) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bromide (mg/L) | 0.16 | nm | 0.21 | 0.23 | 0.10 | 0.45 | 0.15 | 0.26 | NM |
| Calcium (mg/L) | 73 | 120 | 82 | 92 | 46 | 120 | 24 | 110 | 66 |
| Chloride (mg/L) | 29 | 66 | 38 | 64 | 7.1 | 180 | 40 | 120 | 43 |
| Conductivity at 25 C (mS/m) | 55 | 96 | 57 | 79 | 50 | 110 | 51 | 100 | 60 |
| Iron (mg/L) | 0.12 | 0.35 | <0.12 | 0.33 | 0.33 | 1.7 | 0.27 | 1.2 | 0.15 |
| Magnesium (mg/L) | 7.4 | 13.0 | 8.4 | 12.0 | 6.2 | 18 | 7.3 | 13 | 10.0 |
| Manganese (mg/L) | 0.08 | 0.04 | <0.04 | <0.04 | 0.06 | 0.11 | 0.13 | 0.11 | 0.09 |
| Nitrate Nitrogen (mg/L) | 10.6 | <0.025 | 2.7 | 2 | <0.025 | 2.1 | <0.025 | 0.1 | 0.1 |
| Potassium (mg/L) | 2.6 | 4.7 | 2.4 | 3.0 | 2.2 | 2.6 | 3.0 | 2.8 | 2.5 |
| Reacitve Silica (mg $SiO_2$) | 19 | 31 | 19 | 17 | 20 | 25 | 17 | 22 | 19 |
| Sodium (mg/L) | 24 | 45 | 30 | 46 | 42 | 74 | 70 | 72 | 34 |
| Sulphate (mg/L) | 12 | 44 | 15 | 40 | 29 | 74 | 25 | 60 | 35 |
| Total Hardness (mg $CaCO_3$/L) | 213 | 353 | 240 | 279 | 140 | 374 | 90 | 328 | 206 |
| Total Dissolved Solids (TDS)** | 408 | 774 | 428 | 597 | 363 | 818 | 397 | 731 | 470 |

Notes:
"nm" means not measured
(*) asterick indicates well was sampled by CRC Environmental Water Quality Section
**Total Dissolved Solids estimated by summing all the ion concentrations (Fetter, 1994)
[yellow] Exceeds NZ Drinking Water 1995 Aesthetic Guidelines
[orange] Exceeds NZ Drinking Water 1995 Maxiumum Acceptable Values for Health

Figure 5.2a - Distribution of Major Cation Concentrations (mg/l) for Well Sampling Sites and Waipara River Sampling Sites

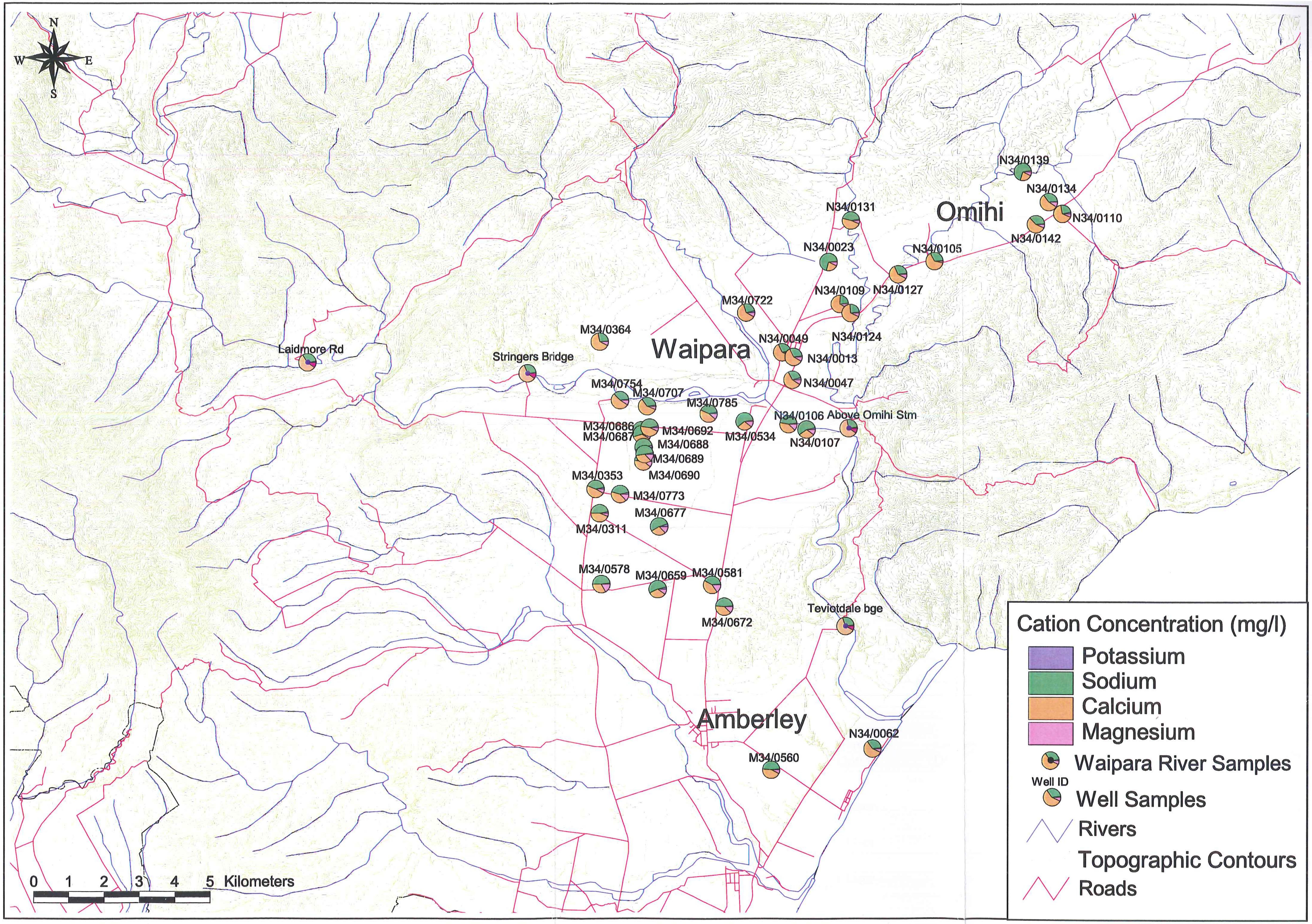
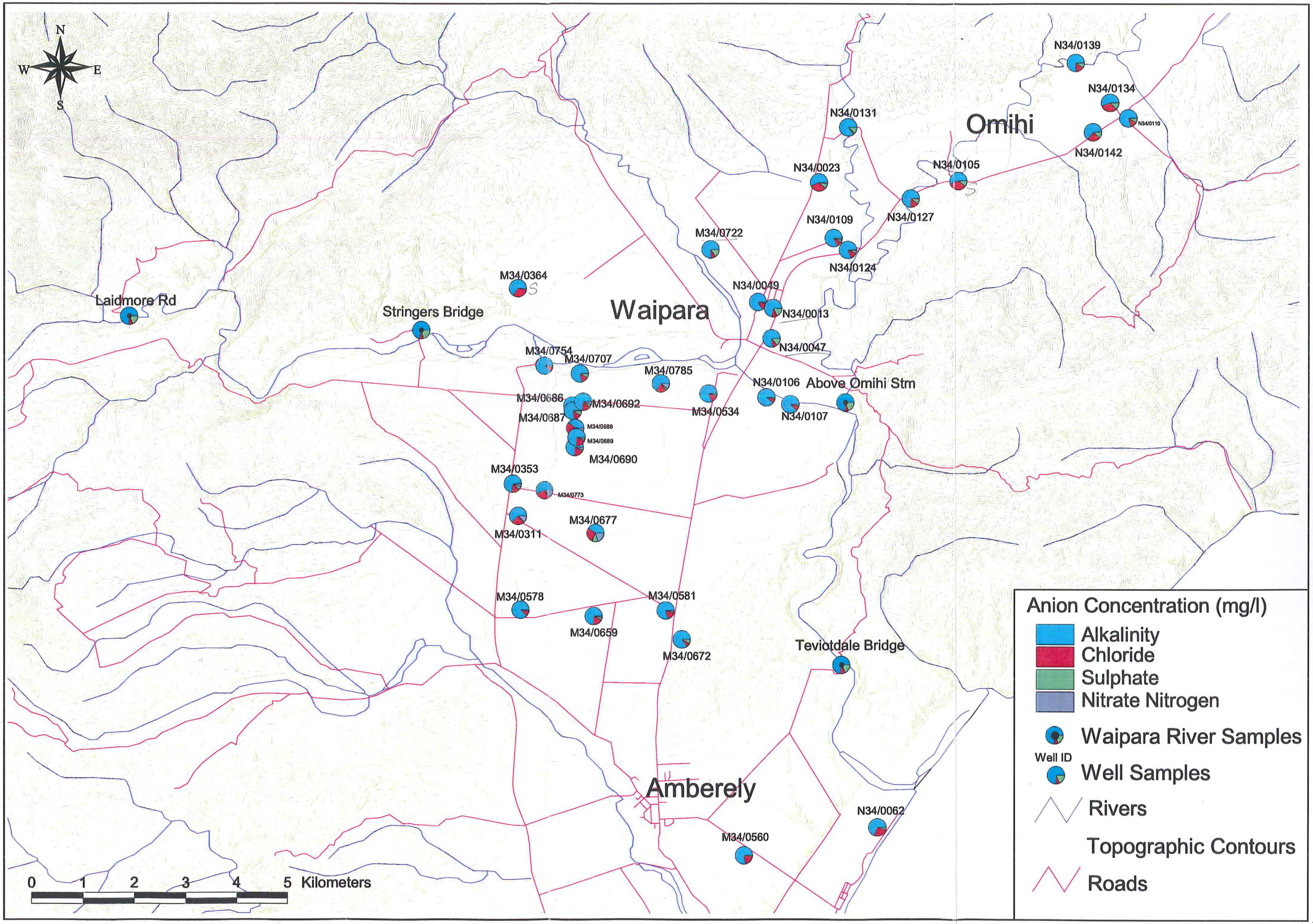


Figure 5.2b - Distribution of Major Anion Concentrations (mg/l) for Well Sampling Sites and Waipara RIver Sampling Sites



(Waipara and Omihi) contain higher concentrations of calcium. Regional trends are difficult to identify when comparing anion concentrations because all Waipara groundwaters (with the exception of two – M34/0677 and N34/0105) are bicarbonate type waters.

Comparison of aquifer cation concentrations with cation concentrations from Waipara River samples show that the aquifers south of the Waipara River (excluding the samples from the wells M34/0754, M34/0707, M34/0785) are different. In addition, comparisons of anion concentrations show that the only samples similar to the chemistry of the Waipara River samples are N34/0013, N34/0047 and M344/0722. The observed trend provides further evidence that the Waipara River is not actively recharging the groundwater system, as previously suggested from the river gauging results presented in Chapter Four.

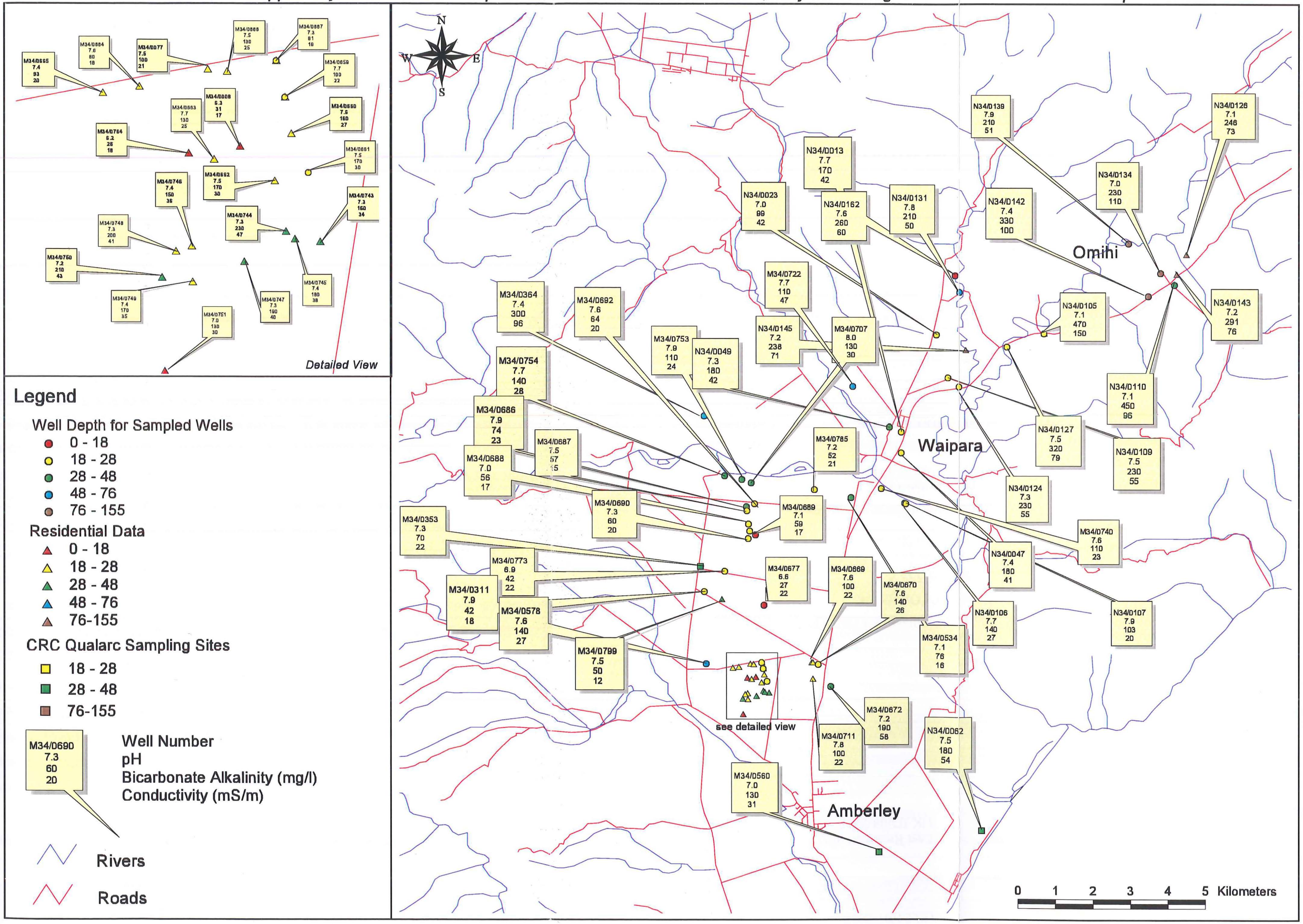
#### *5.3.1.1 pH, Alkalinity and Conductivity*

Figure 5.3 shows the spatial distribution of pH, alkalinity and conductivity throughout the region. Compiled data includes samples collected during this study, data supplied by the residents of the Waipara region, and from the ECAN Environmental Quality Monitoring section. Data presented in Figure 5.3 has been tabulated and included in Appendix E-3.

##### 5.3.1.1.1 pH

The reported pH values for Waipara groundwaters are within the accepted range according to the 1995 DWSNZ guidelines. Samples exhibiting low pH values (< 7.0) were M34/0677 (11.0 m), M34/0773 (25.3 m) and M34/0688 (27.7m), and based on the relatively high concentrations of nitrate-nitrogen (Table 5.1), the low pH values are indicative of degradation of the quality of the groundwater. In addition, the low pH values, and presence of high nitrate concentrations suggest that recharge is occurring through surface infiltration. Measured pH values for other samples range from 7.0 (M34/0311, M34/0689, N34/0023, N34/0134) to 8.0 (M34/0707), and examination of the pH values and relative well depths shows that there is no obvious correlation between pH and aquifer depth.

*Figure 5.3 - Distribution of ph, Conductivity and Alkalinity for Sampled Aquifers. Site marked by circles were sampled by the writer. and sites marked by traingles indicate that the data was supplied by the well owner. Squares show ECAN Environmental Quality Monitoring sites. Colors indicate well depths.*



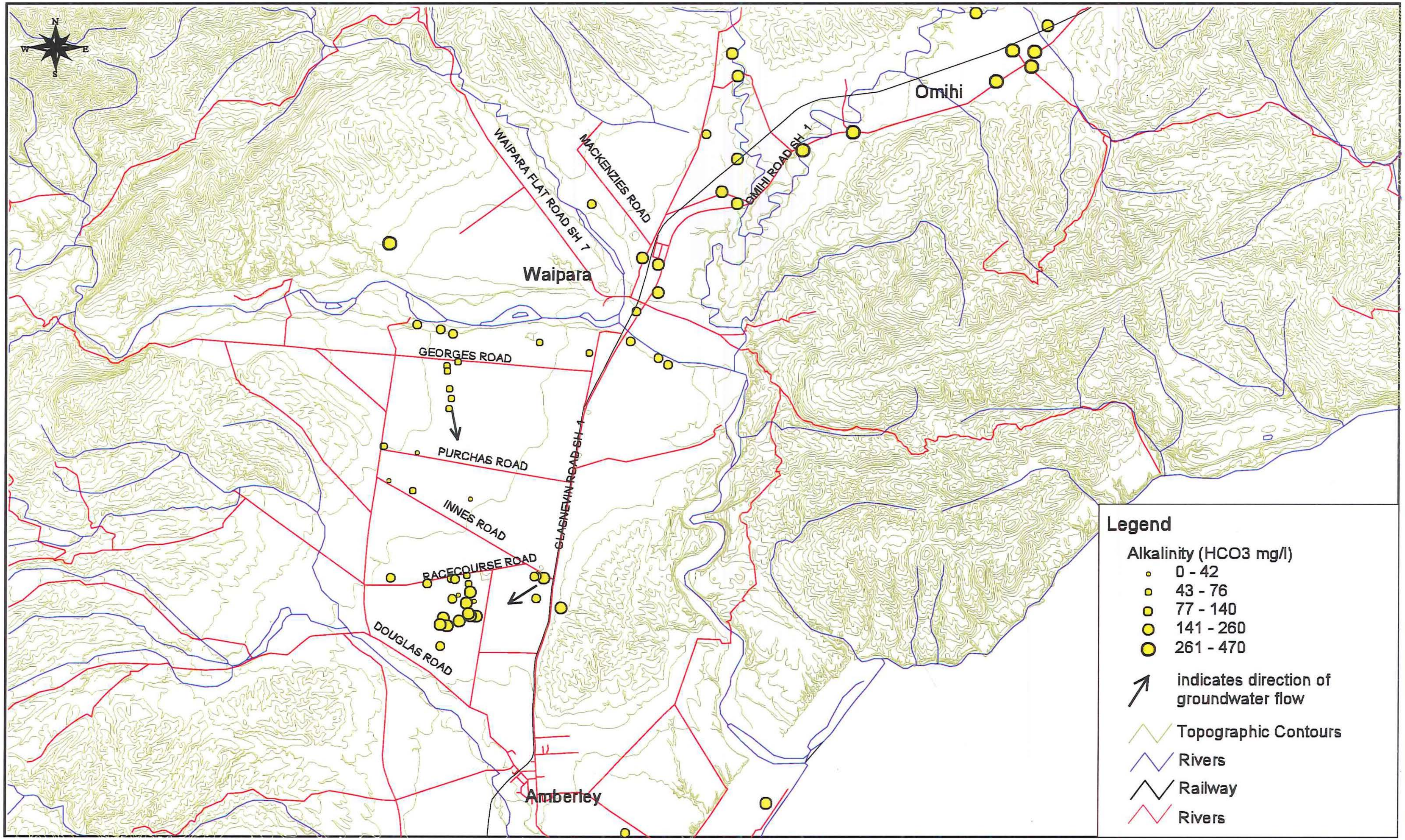
5.3.1.1.2 Alkalinity and Conductivity

Concentrations of bicarbonate alkalinity range from 27 mg/l (M34/0677) to 470 mg/l (N34/0105). Figure 5.4 shows that the concentrations of alkalinity are greatest in Omihi, and based on the abundance of limestone derived clasts identified in drill cuttings and exposed limestone outcrops along the margins of the basin, the high alkalinity signifies that a significant amount of groundwater recharge is derived from the limestone hills along the margins of the basin. Well N34/0105 shows the highest concentration of bicarbonate in the basin, and is attributed to its close proximity to the hills. Figure 5.5 shows limestone exposed in a gully approximately 500 metres upgradient of well N34/0105. Typically, Omihi well samples that exhibit the highest alkalinities, also tend to exhibit the highest conductivities and total dissolved solids (TDS), which suggests that the residence time of the groundwater is long, which may indicate that there are extensive subterranean caverns formed within limestone.

Alkalinity concentrations south of the Waipara River are variable, ranging from 27 mg/l to 230 mg/l (M34/0744) to 27 mg/l (M34/0677). The wells located along the lower terrace of the Waipara River all exhibit similar concentrations of alkalinity. The most obvious difference is between the wells located along Georges Road and the wells south of Racecourse Road. Based on the geographic distribution of alkalinity concentrations and the established groundwater flow direction (Chapter Four), it has been concluded that the southern most group of wells located along Racecourse Road are being recharged from the eastern margin of the basin from the Cass Anticline, which is composed of folded Tertiary rocks at the core. The low alkalinity concentrations exhibited by the shallow Racecourse Road wells (Figure 5.2) suggests that recharge is occurring primarily from surface infiltration of local precipitation. In addition, the groundwater flow direction established in Chapter Four for the Georges Road wells suggests that the intermediate concentrations exhibited by some of the Racecourse Road wells (M34/0664, M34/0665, M34/0077, M34/0666, M34/0667) may be recharging from the both the northwest and eastern margins of the basin, thereby representing a zone of mixing.

Evaluation of Table 5.1 alkalinity values and respective well depths indicates that there

*Figure 5.4 - Geographic Distribution of Alkalinity throughout the Waipara Basin.*



is no apparent correlation between alkalinity and depth, which is expected given the nature of the development of the hydrogeologic environment. The poor correlation of alkalinity with depth strongly supports the hypothesis that the observed concentrations are a function of geographic location, and indicative of the source of recharge.

***Figure 5.5– Photograph showing limestone outcrop 500 metres east of well N34/0105 (NZMG M34: 94711-96595)***

***(Photo: B.Young)***

### *5.3.1.2 Total Hardness*

Nine samples, all of which were sampled from wells north of the Waipara River exceeded the recommended values for total hardness ($CaCO_3$). The ease or difficulty with which soap lathers reflects the hardness of water. The hardness is caused by the presence of divalent metallic cations, particularly $Ca^{2+}$ and $Mg^{2+}$, which are precipitated from $CO_3^{2-}$ in the presence of $CO_2$ (Lloyd and Heathcote, 1985).

Based on the hardness classification shown in Table 5.2, groundwaters south of the Waipara River tend to be soft, whereas groundwaters north of the Waipara River range from hard to very hard. Total hardness ($CaCO_3$) concentrations range from 38 mg/L of $CaCO_3$ (M34/0534) to 607 mg/L of $CaCO_3$ (N34/0105). Hardness concentrations of 200 – 300 mg/l are indicative that groundwaters have been in contact with limestone, (Hem, 1992). The observed hardness of sampled aquifers is directly related to the

***Table 5.2 – Hardness Classification (mg/L of $CaCO_3$)***

| | |
|---|---|
| 0 – 60 | Soft |
| 61 – 120 | Moderately hard |
| 121 - 180 | Hard |
| More than 180 | Very Hard |

(Hem, 1992)

alkalinity, as the geographic distribution of hardness concentrations is identical to the distribution of alkalinity, which confirms that the alkalinity concentrations are directly related to the presence of limestone. Aquifers containing hard groundwaters have relatively high concentrations of calcium, magnesium, chloride and conductivity, and further reflects the influence of the local geology, aquifer lithology and often residence times of the groundwater.

Hard water does not put anyone at risk for health reasons, but can result in a build-up of precipitates in the pipes and on the heating elements.

*5.3.1.3* *Total Dissolved Solids*

Total dissolved solids (TDS) were calculated by summing the reported ion concentrations (Hem, 1992; Fetter, 1994). The reported bicarbonate ion in groundwater is present in solution, and when TDS are measured in the lab, the TDS are evaporated, causing the bicarbonate ion to be volatilised as $CO_2$ and $H_20$. When calculating TDS from reported ion concentrations, the reported bicarbonate concentrations needs to be converted to carbonate in the solid phase by a factor (mg/L $HCO_3$ x 0.4917 =mg/L $CO_3$), thereby representing the remaining residue if it had been evaporated in the lab (Hem, 1992). The converted value is then summed with the remaining ion concentrations. The calculated TDS may differ by 10-20 mg/l from the value obtained by the measured laboratory value when the concentration of solids is between 100 – 500 mg/l (Hem, 1992). Calculated results (Table 5.1) range from 68 mg/l (M34/534) to 1,244 mg/l (N34/0105). According to the classification scheme presented in Table 5.3, Waipara groundwaters are classified as fresh water, except

*Figure 5.6 - Geographic Distribution of Hardness Concentrations (mg/l) Throughout the Waipara Basin*

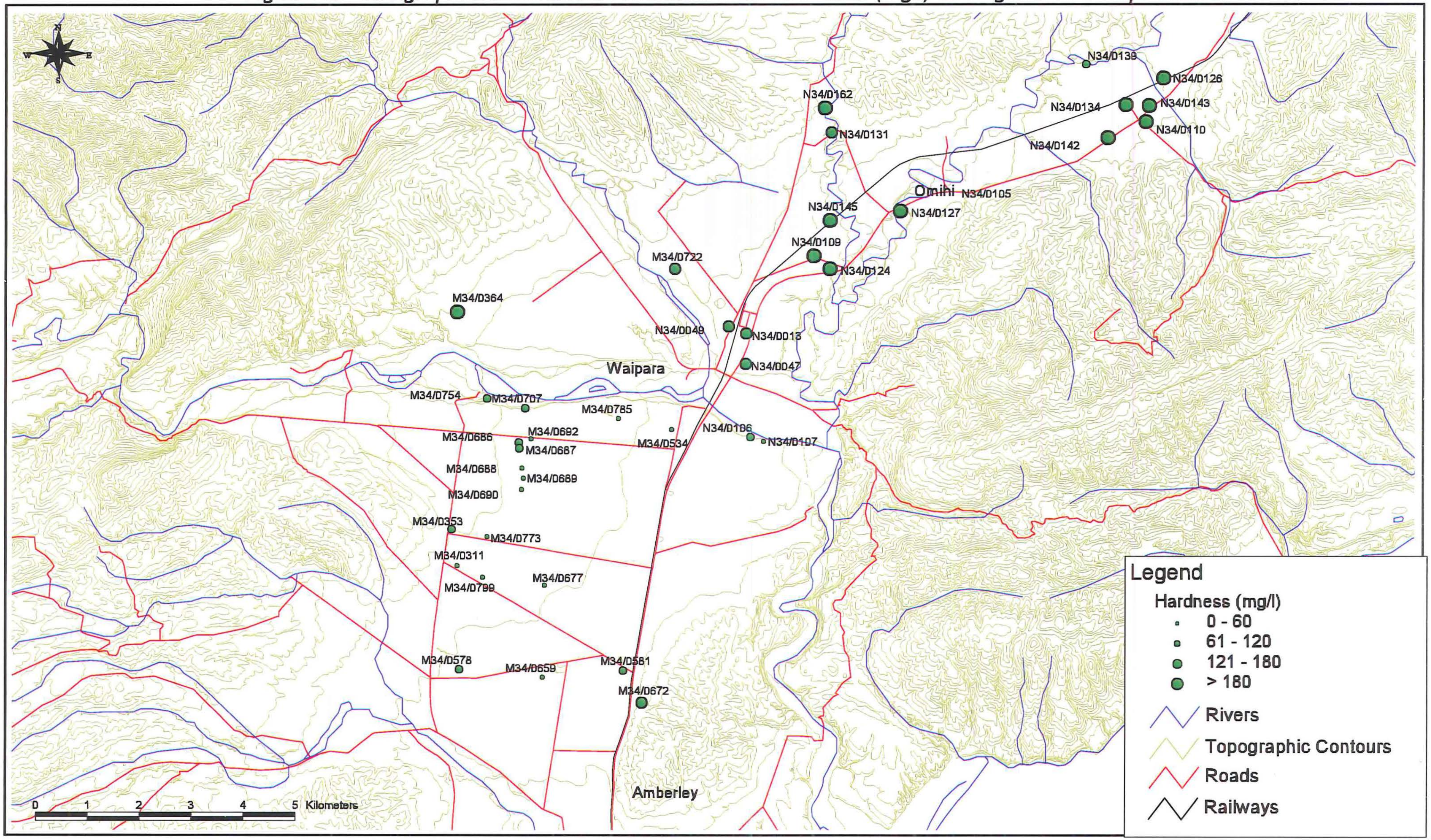


***Table 5.3 - Total Dissolved Solids (mg/l) Classification for Groundwater***

| Classification | Total Dissolved Solids (mg/l) |
|---|---|
| Fresh Water | 0 – 1,000 |
| Brackish Water | 1,000 – 10,000 |
| Saline Water | 10,000 – 100,000 |
| Brine Water | More than 100,000 |

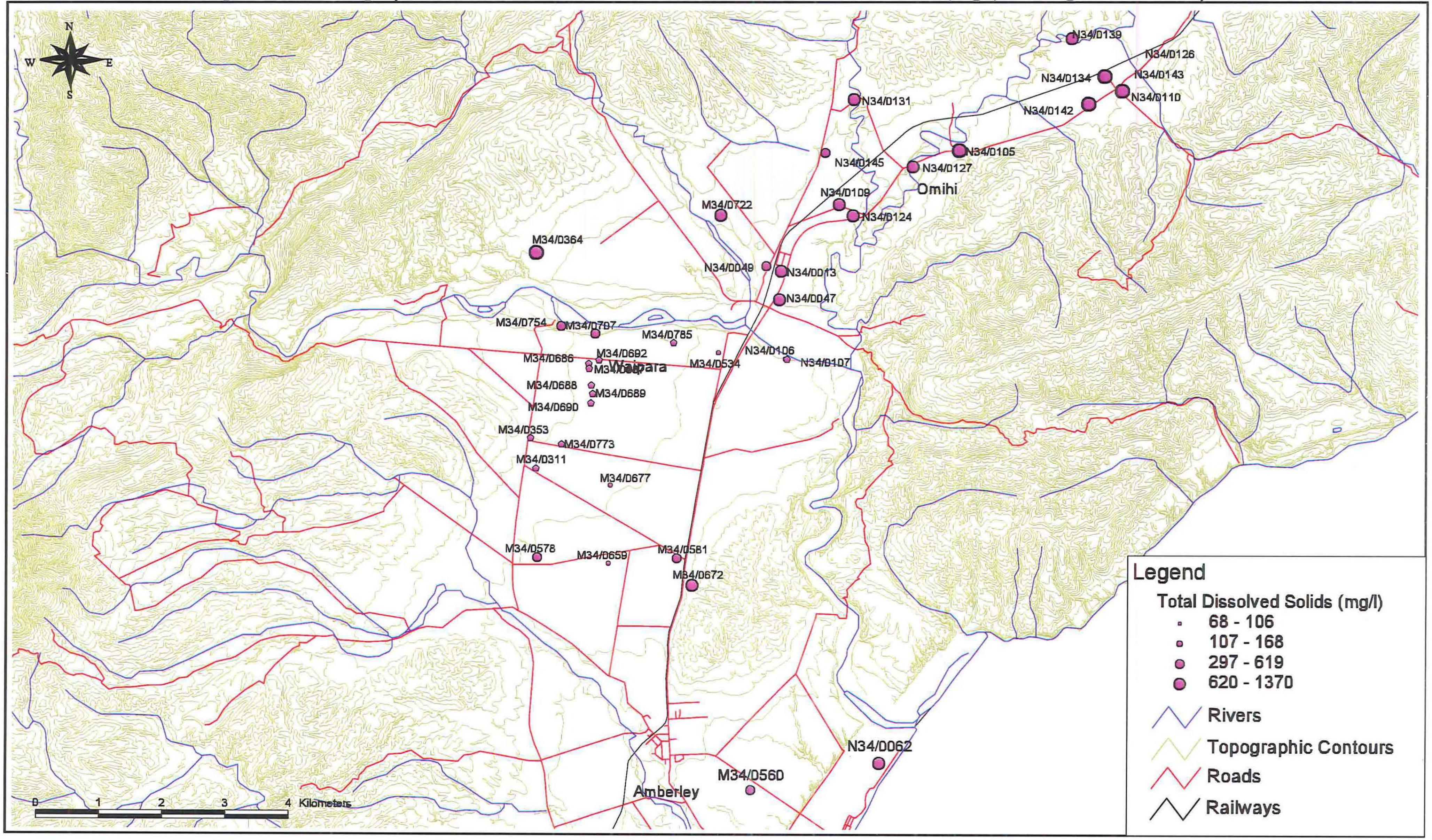
(Freeze and Cherry, 1979)

for N34/0105, which is classified as slightly brackish. Examination of TDS concentrations in Table 5.1 shows that wells located north of the Waipara River, and wells penetrating the deeper aquifers have higher concentrations of TDS, suggesting that they have longer residence times, as groundwater becomes mineralised over time (Lloyd and Heathcote, 1985). Figure 5.7 shows the geographic distribution of TDS throughout the basin. TDS concentrations reflect the influence of the local geology, aquifer characteristics and residence times with in the hydrogeological system. Low TDS concentrations located in the central part of the basin may signify groundwater mixing zones, or regions of different recharge sources (i.e. rainwater recharging through claybound greywacke alluvium versus Tertiary derived gravels, and/or limestone units outcropping along margins of the basin).

#### *5.3.1.4 Nitrate-Nitrogen*

As mentioned previously, three samples exhibited high concentrations of nitrate nitrogen ($NO_3^-$-N), two of which exceeded the 1995 DWSNZ maximum acceptable values of nitrate nitrogen for health risks. Well M34/0677 is a shallow (11.8 metres), windmill driven well used to supply water for stock. It is suspected that most of the shallow aquifers are contaminated with higher than average nitrate concentrations due to the combined effects of downward percolation of surface runoff to the water table and slow flowing groundwater which results in an accumulation of nitrate nitrogen. Natural concentrations in groundwater range from 0.1 mg/l to 10 mg/l. Many of the shallow wells are open brick wells with measuring points at ground level that do not have secure well coverings and/or shelters, increasing the risk of nitrate

*Figure 5.7 - Geographic Distribution of Total Disolved Solids Concentrations (mg/l) Throughout the Waipara Basin*



contamination. Groundwater samples exhibiting significantly higher nitrate concentrations are all located south of the Waipara River. Contamination of the deeper wells (> 20 metres) can result from natural infiltration of contaminated surface water, and/or leakage from septic tanks across a leaky confining unit. Well M34/0688 was sampled in October 1998 by the well owner shortly after development, and the analysis reported a nitrate-nitrogen concentration of 3.8 mg/l. The irrigation season commenced in December 1999. The January 2000 analysis reported nitrate concentrations of 17 mg/l. Because of the discrepancy, the well owner resampled the well in May, and analysis showed nitrate concentrations of 15 mg/l (P. Woods, pers.comm., 2000). In addition, chloride concentrations increased by 2 mg/l. Significant increases in chloride and nitrate concentrations are generally indicative of sewage contamination (Driscoll, 1986). The log from M34/0688 suggests that the aquifer is semi-confined, and the increase in the nitrate concentration is believed to be the effects of pumping drawing water from the overlying shallow semi-confining units. Other wells in the area did not show a significant increase in nitrates, except well M34/0686, which increase from 1.2 in 1998 to 6.0 in 2000, and may be due to natural seasonal variations as the water table rises and falls (S. Hayward, pers.comm., 2000). ECAN laboratory reports for collected samples are included in Appendix E-4.

#### *5.3.1.5 <u>Iron and Manganese</u>*

The high manganese and iron is attributed to weathering of greywacke gravels and glauconitic-rich sediments, particularly in oxygen-depleted environments where manganese is extracted from organic-rich sediments (Hem, 1992). The relatively high concentrations of manganese have been attributed to the influence of the aquifer lithology and the local geologic environment, as much of the Tertiary rocks enriched with glauconite as stated in Chapter Two (Figure 2.1). The higher than average concentrations implies that the groundwater is relatively old, flowing at relatively slow rates and has long residence times, particularly, when groundwaters exhibit both high iron and manganese concentrations (Bouwer, 1978).

In addition, higher than average iron concentrations in the shallower wells can also be attributed to degradation and corrosion of the well casing, and is particularly common with steel casings and highly oxygenated groundwaters. Groundwater samples taken after the Broomfield-Amberley pump test showed an increase in iron, and after the test the discharge pipes had accumulated large amounts of iron flakes and sediment that resembled particles derived from the well casing.

High manganese concentrations and iron primarily affect the potability of the water, resulting in discoloration, build up of precipitated sediments in pipes and irrigation equipment, and producing a noticeable after taste and higher turbidity (Hem, 1992; Driscoll, 1986).

#### *5.3.1.6 Sodium Absorption Ratio*

Figure 5.8 is a sodium absorption ratio (SAR) diagram for sampled Waipara groundwaters. The sodium absorption ratio evaluation was developed by the United States Salinity Laboratory (Hem, 1992) to assess the suitability of groundwater for irrigation purposes. When groundwaters high in sodium, low in calcium and magnesium are applied to soils, the sodium is absorbed by the clays in the soil, which gives up calcium and magnesium ions in exchange. This exchange can alter the physical properties of the soil by reducing the permeability of the soil when wet, and increasing the hardness of the soil when dry (Rhoades, 1972). The SAR is calculated from the following equation:

$$\boxed{SAR = \frac{Na}{((Ca + Mg)/2)^{1/2}}} \qquad [5.1]$$

where sodium, magnesium and calcium are in milliequivalents per litre. SAR calculations were completed with the Groundwater for Windows (GWWA, 1998) computer software program. In addition, calculated values were plotted on a Wilcox diagram in GWWA in order to classify and rate the suitability of the water for irrigation purposes. All Waipara groundwaters are low in SAR ratio, falling within the low category (S1) for potential sodium hazard. However, Waipara groundwaters show a wide range of salinity concentrations (conductivity, measured as millisiemens per metre (mS/m) for which 1 mS/m = 10 microhos/cm, see Appendix E-5). Five samples

(M34/0364, N34/0105, N34/0110, N34/0134 and N34/0145) have a high concentration of magnesium and calcium, relative to sodium, resulting in a high salinity hazard classification (C3). High salt concentrations can inhibit the crop growth by altering the soil structure, permeability and drainage, soil aeration, and the plant's metabolic processes (Rhoades, 1972). Groundwaters that fall within the C3 classification should not be used on poor draining soils (Driscoll, 1989), without special care and considering whether or not the crop of choice has adequate tolerance to salinity. Groundwaters south of the Waipara tend to exhibit lower SAR values. The low SAR values and conductivity values exhibited by the southern region wells are explained by the decrease in calcium and magnesium concentrations.

## *5.4 Groundwater Classification*

### 5.4.1 Graphical Presentation of Chemical Analyses

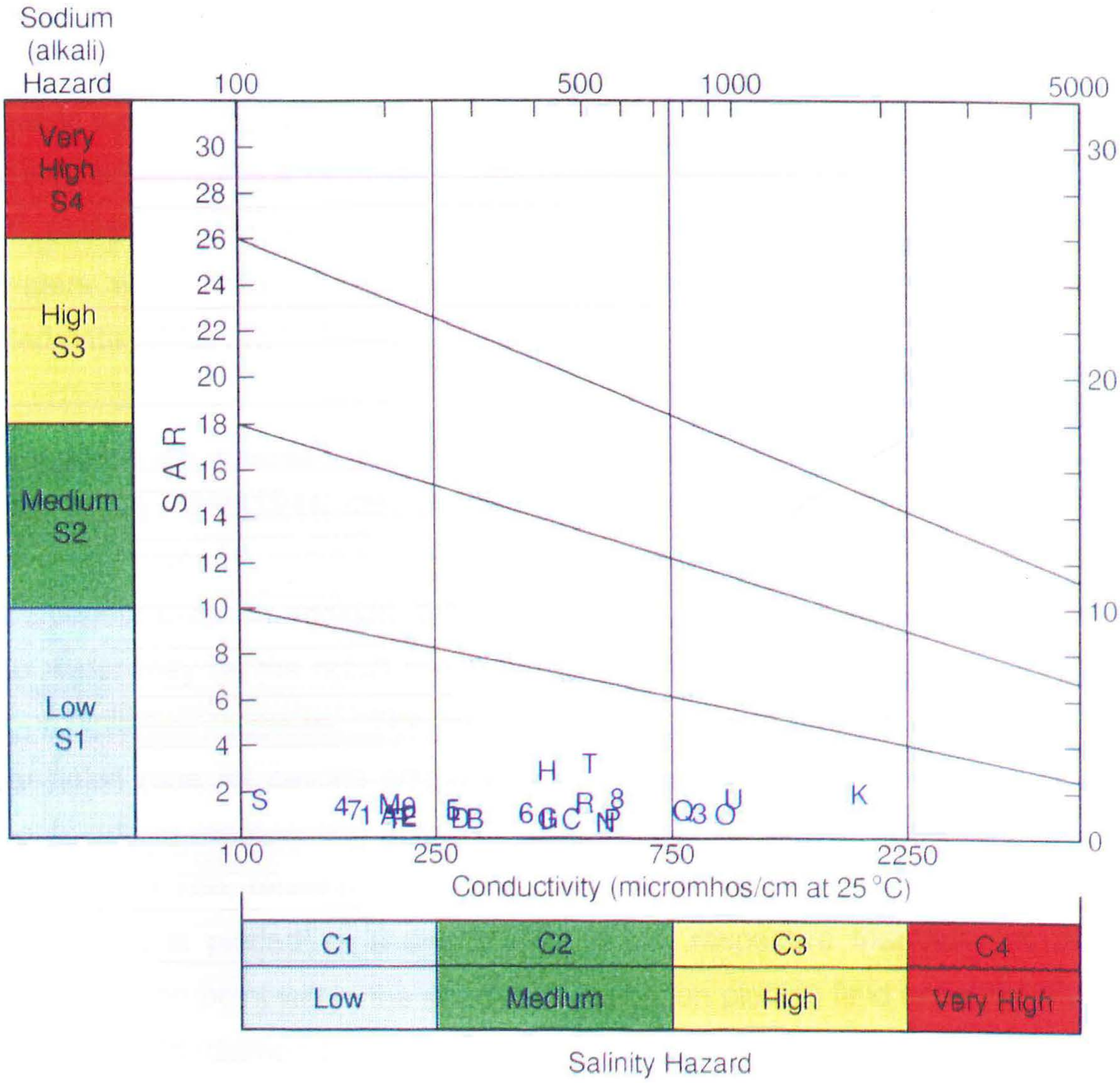
Two methods of presentation of chemical analyses were used to aid in the identification, evaluation and classification of chemical analyses. The two methods of graphical analyses were chosen because they are the most widely used methods by hydrogeologists for the evaluation of groundwater chemistry and identification of relationships between sampled aquifers.

#### *5.4.1.1 Methodology and Application of Stiff Plots*

The Stiff method of representing hydrochemical data uses four parallel horizontal axes, extending on each side of a vertical axis by a given amount from zero. Each axis corresponds to a cation/anion pair (i.e. Na+K – Cl; Ca – $HCO_3$; Mg – $SO_4$, and Fe – $NO_3$). The respective ionic concentrations (in milliequivalents per liter) are plotted accordingly, and the resulting points are connected which gives rise to an irregularly shaped polygon. The distinctive pattern produced is indicative of a particular groundwater type (i.e. calcium bicarbonate, sodium sulphate) because the width of the pattern is a reflection of the relative ionic concentrations (Lloyd and Heathcote, 1985; Fetter, 1994).

The groundwater classification nomenclature is based on identifying the dominant cation and anion. However, in many situations the relative concentration of the cations

*Figure 5.8 - Sodium Absorption Ratio (SAR) Diagram*




<u>Sample Identification Key</u>

| | | | |
|---|---|---|---|
| 1 M34/0311 | A M34/0692 | J N34/0049 | S N34/0134 |
| 2 M34/0353 | B M34/0707 | K N34/0105 | T N34/0139 |
| 3 M34/0364 | C M34/0722 | L N34/0106 | U N34/0142 |
| 4 M34/0534 | D M34/0754 | M N34/0107 | |
| 5 M34/0578 | E M34/0773 | N N34/0109 | |
| 6 M34/0581 | F M34/0785 | O N34/0110 | |
| 7 M34/0659 | G N34/0013 | P N34/0124 | |
| 8 M34/0672 | H N34/0023 | Q N34/0127 | |
| 9 M34/0677 | I N34/0047 | R N34/0131 | |

and the anions may be present in equal or close to equal concentrations, in which case no dominant water type can be assigned. Hem (1992) suggests that for waters in which the relative cation concentrations and anion concentrations do not differ by more that 50%, classification and naming of the groundwater type should be avoided. Groundwater in which no dominating cation or anion can be identified are interpreted to have evolved as a result of mixing. Stiff plots are excellent for plotting numerous chemical analyses from a region because the plots of similar shape represent groundwaters with similar characteristics and sources. Individual Stiff plots and associated data tables are included in Appendix E-6.

#### *5.4.1.2 Methodology and Applications of Piper Diagrams*

Application of the Piper (1944) method for the evaluation of hydrochemical data is used for comparing numerous samples to classify groundwaters in terms of hydrochemical facies (Appendix E-7). In addition, the Piper diagram can aid in assessing whether a particular water may be the result of mixing of other waters, or has been affected by solution-precipitation reactions. The trilinear diagram utilises three plotting fields: two triangular fields (one for cations and one for anions) and a diamond shaped field in which each side is representing a pair of cations or anions. Each field has a scale ranging from 0 to 100, representing a percentage of the total ions. Each anion and cation proportion is plotted as a single point in the respective triangles. A ray is extended from each point within the anion and the cation plotting field upwards into the central plotting field (diamond), and the point of intersection between the two projected rays represents the water type. Mixtures of waters will plot on a straight line between two components in the plotting field, as long as the two ions do not react chemically as a result of mixing. However, if two plotted analyses define a straight line in the direction of one of the cation/anion vertices, the point representing the more concentrated water has been affected by the addition of the given cation/anion component (i.e. salt).

### 5.4.2 Groundwater Classification

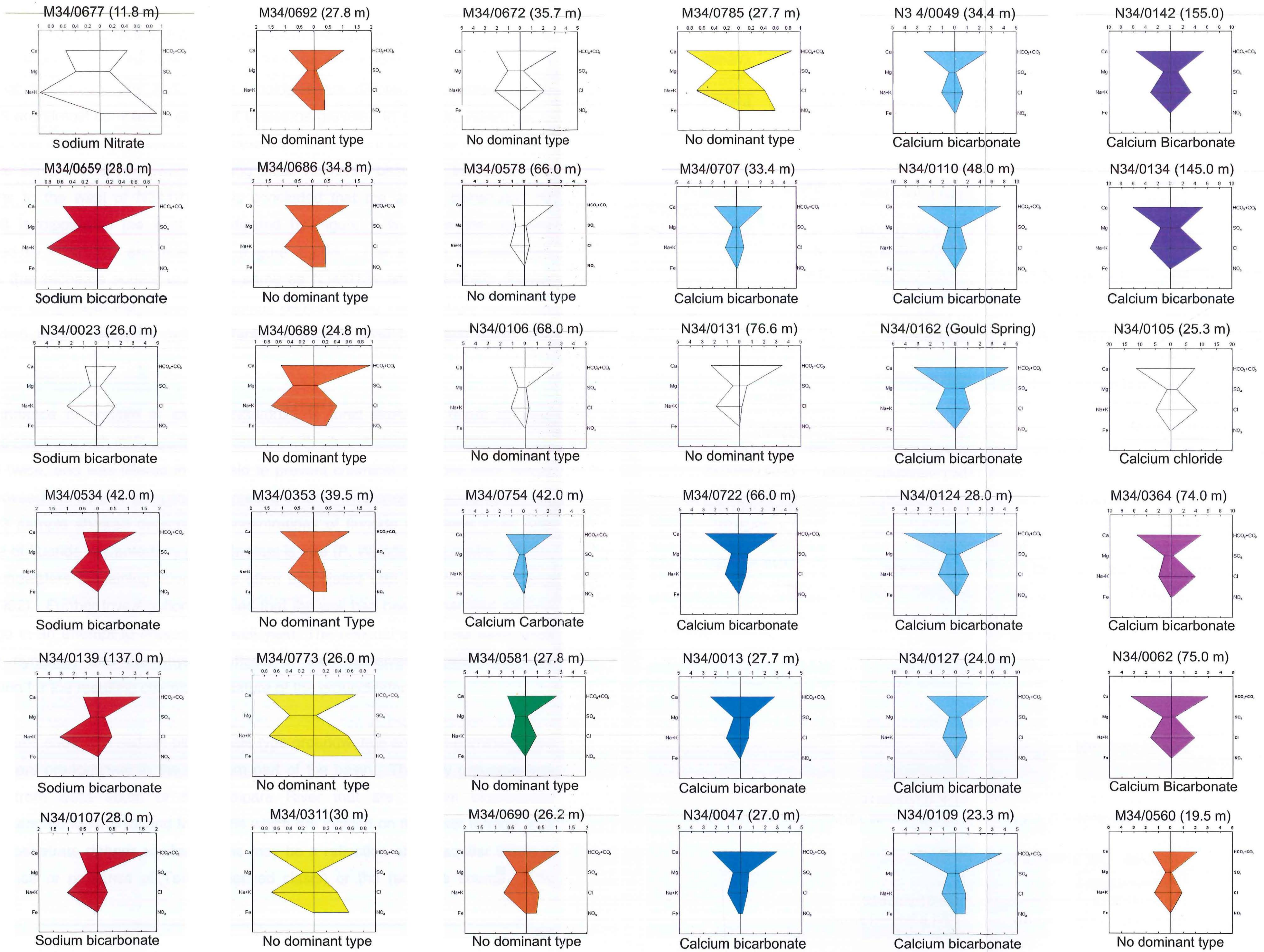
#### *5.4.2.1 Stiff Plots*

Figure 5.9 shows Stiff plots for selected chemical samples. Stiff diagrams were constructed with the computer software program Groundwater for Windows (GWWA, 1997). The program automatically determines the type of groundwater by identifying the dominant anion and cation. Examination of Stiff plots show that groundwaters can be classified into three main groups: sodium bicarbonate type, calcium bicarbonate type, and non dominant type waters, which do not exhibit any dominant chemical characteristic. "Non-dominant" groundwaters most likely signify that mixing of waters derived from different recharge sources has occurred.

All groundwaters sampled are of the bicarbonate type with the exception of N34/0105, and M34/0677. Groundwater sampled from N34/0105 (25.3 m) is classified as a calcium chloride type water. The high calcium and bicarbonate concentrations exhibited by N34/0105 are attributable to the dissolution of limestone due to the chemical weathering process. However, the high chloride concentration may be the result of contamination from anthropogenic sources (i.e. fertilisers, sewage), however, evidence for contamination from these sources has not been found. The third anomalous water type was sampled from M34/0677 (11.0 m), and is classified as sodium nitrate water. Given the shallow depth of the well, the high concentration of chloride and nitrate is an indicator that the groundwater has been contaminated from a variety of sources (i.e. septic tanks, stock and fertilisers) (Driscoll, 1986). Examination of the Stiff plot for M34/0677 indicates that if the effects of contamination were removed, the groundwater would most likely represent the sodium bicarbonate type.

Sodium bicarbonate type groundwaters were sampled from a wide range of aquifer depths, occurring in both the northern and southern regions of the basin (Figure 5.2a). The majority of the aquifers sampled north of the Waipara River are calcium bicarbonate type, with the exception of N34/0131 (no dominant type), N34/0139 (sodium bicarbonate), N34/0023 (sodium bicarbonate) and N34/0105 (calcium chloride). Samples collected from N34/0134 (145.0 m) and N34/0142 (155.0 m), located to the east and southeast of N34/0139, penetrate aquifers of similar depths, but are classified as calcium bicarbonate waters. Although, N34/0134 and N34/0142 contain multiple screens, the Stiff diagrams do not exhibit a shape indicative of mixing of sodium bicarbonate and calcium bicarbonate type waters (i.e. no dominant water

*Figure 5.9 - Stiff Plots for Selected Sampled Aquifers*



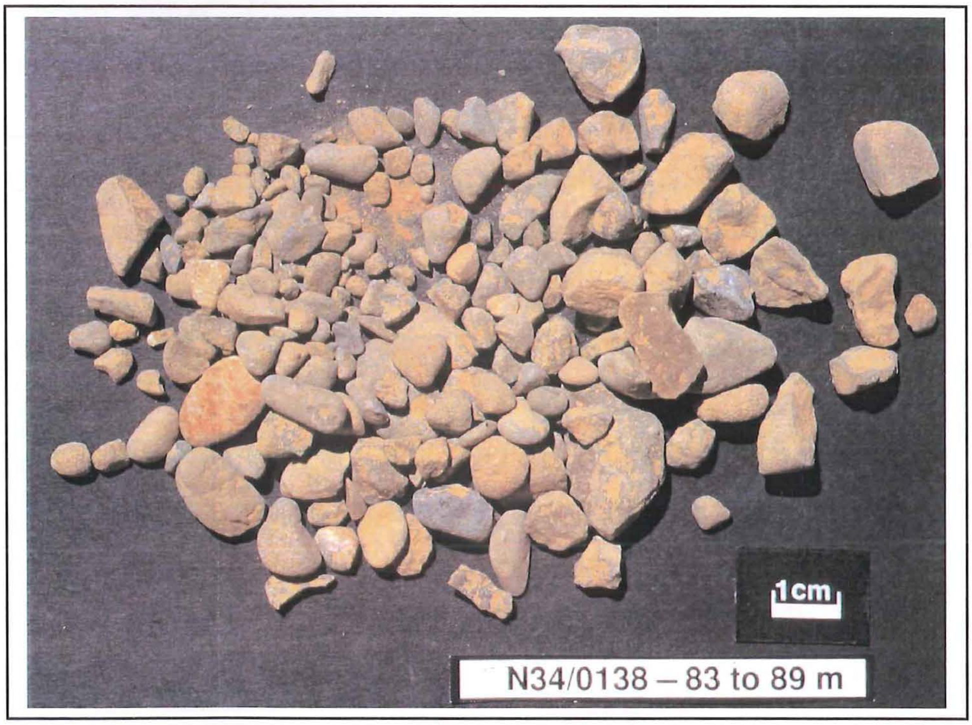
type). The different chemical signatures reflect both the aquifer lithology, and source of recharge. Evaluation of the well logs for N34/0134 and N34/0139 (Appendix B-1) shows that the stratigraphy and aquifer lithologies are different, as samples from N34/0139 are almost completely devoid of limestone gravels. In addition, N34/0134 is screened over 40 metres of strata, and therefore the resultant chemistry represents a composite sample of several water-bearing units. However, based on the dip of the formations to the west of N34/0139, it is concluded that the aquifer penetrated by N34/0139 is dipping to the east as indicated by Figure 1.3a, below the aquifers penetrated by N34/0139 and N34/0142 (Figure 4.21b). The sodium concentration indicates that recharge source is not the same as N34/0134 and N34/0142. Figure 5.10 shows samples of the respective aquifers demonstrating the lithologic variability. The relative height difference with reference to ground level has been taken into account.

The abundance of sodium in sample N34/0023 is most likely the result of ionic exchange reactions with ionic species associated with silt and clay. Well N34/0023 was sampled twice, and was filtered in the field to prevent chemical reactions from taking place between the time of sampling and measurement. The chemical analysis for the N34/0023 sample showed detectable concentrations of fluoride (Appendix E-4). The presence of fluoride in Canterbury groundwaters is rare (P. Woods, pers.comm., 2000), and groundwaters containing fluoride are often associated with hydrothermal activity (Hem, 1992). Further investigation revealed that the well had been dynamited several years ago in an attempt to improve the well yield. The residual chemicals associated with the dynamite and the physical effects of the explosives, provide the best explanation for the resulting chemical signature of the groundwater.

Stiff diagrams show that sodium bicarbonate type groundwaters and non-dominant type groundwaters predominate in the southern part of the basin. The only groundwaters sampled from wells south of the Waipara River that are calcium bicarbonate groundwaters are M34/0707 and M34/0754 which are located on the lower terrace, and therefore penetrate deeper aquifers. This may be a reflection of the aquifer lithology (i.e. absence or presence of Tertiary derived clasts) or the recharge source. The

***Figure 5.10 – Photographs of Lithologic Samples from Drill Cuttings for Wells N34/0134, N34/0139 Showing Weathering of Gravel Aquifers***


*a) N34/0134*




*b) N34/0139*

deeper aquifers may be recharged from water percolating through the limestone hills compared to the shallow aquifers, which may be recharged by infiltration of local rainfall in the unconfined region of the aquifer. The predominance of the non-dominant type groundwaters suggests that most of the groundwater is of mixed origin. Sodium bicarbonate type waters appear to be confined to the aquifers contained in the top 42 metres of the substrata, and do not exhibit any recognisable pattern in terms of geographic distribution. 'No dominant type' groundwaters occur in aquifers between 24.8 metres (M34/0689) and 66.0 metres (M34/0578). Samples collected from wells penetrating deeper aquifers on the lower terrace on the south side of the Waipara River (M34/0754, M34/0753 and N34/0106) do not exhibit any dominant type of groundwater, and most likely reflects the effects of dilution and mixing. Only one sample collected from the south side of the Waipara River is of the calcium bicarbonate type (M34/0707), which may reflect the influence of the aquifer lithology in facilitating the dissolution of calcium (Lloyd and Heathcote, 1985).

Correlation of aquifers within the three classification groups has been attempted based on similar polygon shape. Correlated aquifers are indicated by colour in Figure 5.9. Groundwaters that could not be correlated are white in colour. Examination of the aquifer correlation shows that the aquifer chemistries are greatly influenced by the local geology and sources of recharge. In addition, the geographic distribution of groundwaters that are of the 'no dominant type' is limited to the central and southern region (except for N34/0131). This suggests both the shallow and deep aquifers south of the Waipara River are being recharged from a variety of sources.

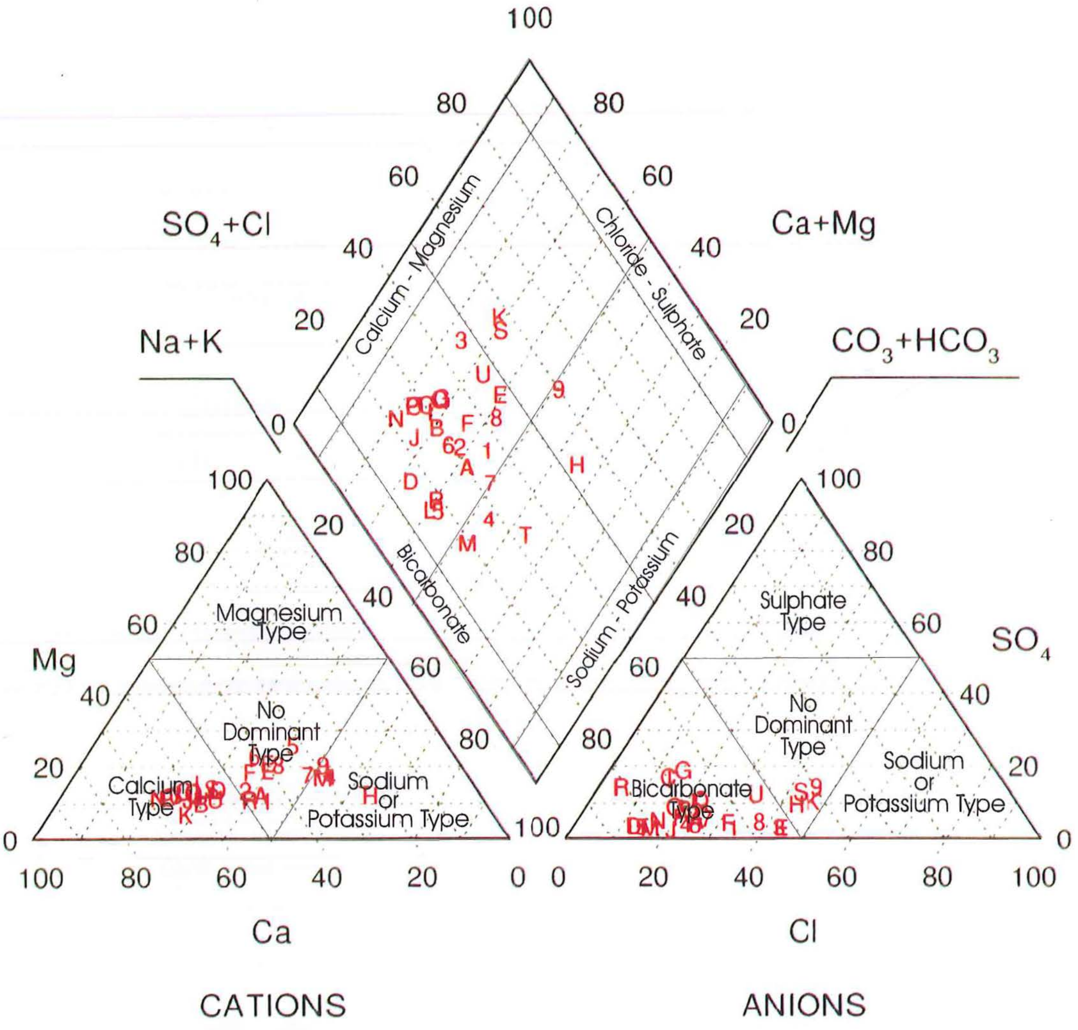
#### *5.4.2.2 Piper Diagrams and Hydrochemical Facies Classification*

Selected sample analyses are plotted in a Piper trilinear diagram in Figure 5.11. As shown by the Stiff plots, all samples are bicarbonate type water with the exception of N34/0139 (S), N34/0105 (K), N34/0023 (H) and M34/0677 (9), which cannot be characterised as a particular type water, and plot in the "no dominant type" anion field. Samples N34/0139 and N34/0023 had been previously classified as bicarbonate type waters by the Stiff method, demonstrating the limitations of the Stiff method, and the limitations of analysing chemical data with Groundwater for Windows.

Samples plot in the calcium type, sodium/potassium type, and in the no dominant type cation fields. In the main field, the majority of the groundwaters fall within the bicarbonate-chloride-sulphate field, with M34/0105(K), M34/0677(9), N34/0023(H), and N34/0134(S) included in the chloride-sulphate, and bicarbonate facies field. Groundwaters with long residence times in a hydrogeological system show an increase in total dissolved solids (TDS) and chloride concentrations as mineral leaching is the dominant chemical activity (Chebotarev, 1955). The high chloride concentrations measured in M34/0667 and N34/0023 are attributed to contamination by anthropogenic activities, whereas the high chloride and TDS concentrations (Table 5.1) exhibited by N34/0134 and N34/0105 samples may signify long residence times in the hydrogeologic system. Samples N34/0142(U) and M34/0364(3) plot close to the chloride-sulphate-bicarbonate field, and Table 5.1 shows that the high chloride concentrations are complemented by high TDS concentrations. Sample M34/0773(E) plots close to the chloride-sulphate-bicarbonate field, but the high nitrate concentrations, low TDS and shallow aquifer depth are indicative of contamination rather than a long residence time.

Samples N34/0124 (P) and N34/0110 (O), and N34/0013 (G) and N34/0127 (Q) plot on the same spot suggesting that the wells are penetrating the same aquifer, or that the recharge source is the same. Wells N34/0110 and N34/0124 are located over 5 kilometres away from one another, and given the nature of the hydrogeological development of the region, the two aquifers are most likely separate. Regional groundwater flow from Omihi is estimated to be towards the southwest, and the Stiff plots in Figure 5.9 correlate well with one another, suggesting that the aquifer penetrated by N34/0124 is being recharged from the northern part of the valley. In addition, samples N34/0013 and N34/0127 plot in the same location further suggesting that the central Waipara region is being recharged from the northern part of the basin. Examination of Stiff plots in Figure 5.9 show the groundwaters to be slightly different, which may reflect local variations in aquifer lithology and clay content. Poorly constrained potentiometric surface maps presented in Chapter Two suggests that the regional flow direction is to the south, and the groundwater chemistry appears to correlate well with the constructed potentiometric surface maps and estimated direction

## *Figure 5.11 - Piper Trilinear Plot of Selected Samples*




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | M34/0311 | 9 | M34/0677 | H | N34/0023 | P | N34/0124 |
| 2 | M34/0353 | A | M34/0692 | I | N34/0047 | Q | N34/0127 |
| 3 | M34/0364 | B | M34/0707 | J | N34/0049 | R | N34/0131 |
| 4 | M34/0534 | C | M34/0722 | K | N34/0105 | S | N34/0134 |
| 5 | M34/0578 | D | M34/0754 | L | N34/0106 | T | N34/0139 |
| 6 | M34/0581 | E | M34/0773 | M | N34/0107 | U | N34/0142 |
| 7 | M34/0659 | F | M34/0785 | N | N34/0109 | | |
| 8 | M34/0672 | G | N34/0013 | O | N34/0110 | | |

of groundwater flow.

## 5.5 Environmental Isotopes for Dating of Groundwater

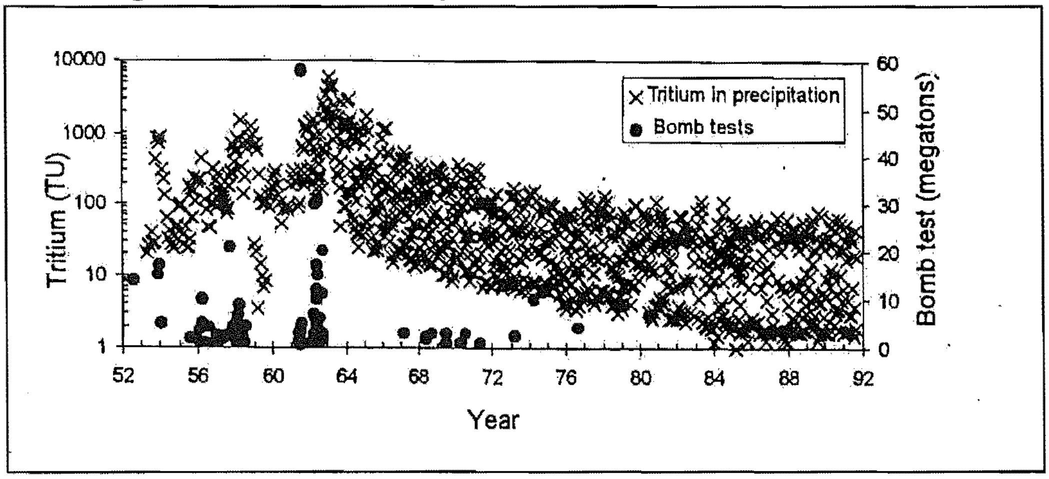
Groundwater sampling for isotopic analysis was completed in April 1999 and February 2000 to determine the age of the groundwater (i.e. date of recharge), and to constrain the sources of groundwater recharge. Three environmental isotopes were used: tritium ($^3H$), chloroflurocarbons (CFC-11 and CFC-12), and oxygen-18 ($^{18}O$). A brief description of how the three isotopes are used for dating is given in the following sections. A more detailed discussion can be found in Clark and Fritz (1997).

### 5.5.1 Methods of Dating

#### *5.5.1.1 Tritium ($^3H$)*

Prior to 1954, the concentrations of naturally occurring tritium measured in precipitation were low (~5-20 TU, tritium units). However, after 1954, concentrations in the atmosphere and precipitation dramatically increased due to the testing of thermonuclear weapons (Figure 5.12). Various studies demonstrated that the "peak"

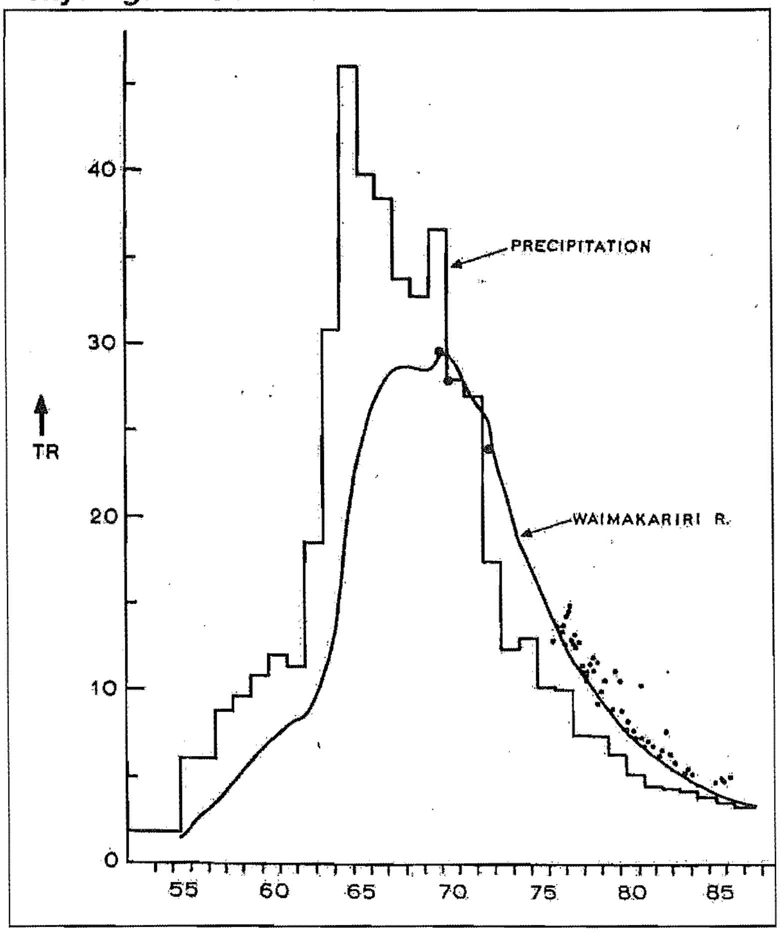
***Figure 5.12 - Tritium levels measured in precipitation from selected Northern Hemisphere stations and measured tritium levels in the atmosphere from nuclear bomb testing Clark and Fritz, 1997).***




could be used as a tool for dating groundwater and recharge events in a hydrogeological system because the $^3H$ isotope does not undergo any form of fractionation (Kaufman and Libby, 1954; Begemann and Libby, 1957; Brown, 1961;

Clark and Fritz, 1997). The correlation of the tritium concentrations preserved in groundwater relative to the bomb-peak enables the identification of the residence time of the groundwater (i.e. recharge year). Naturally occurring tritium (geogenic) in groundwater is present in minute concentrations and is negligible, therefore, measurable $^3H$ in groundwater always signifies groundwaters that have been recharged since the 'peak period.' Figure 5.13 shows the increase in tritium concentrations measured in Kaitoke precipitation compared to measured concentrations in the Waimakariri River from 1952 – 1985. Comparison of the concentration curves in Figures 5.12 and 5.13,

***Figure 5.13 – Measured tritium concentrations in Kaitoke precipitation versus measured tritium in the Waimakariri River from 1952 – 1985 (Taylor et al., 1989). Tritium concentrations are reported as tritium ratio(TR). TR equal to 1 signifies a tritium/hydrogen ratio of $10^{-18}$.***

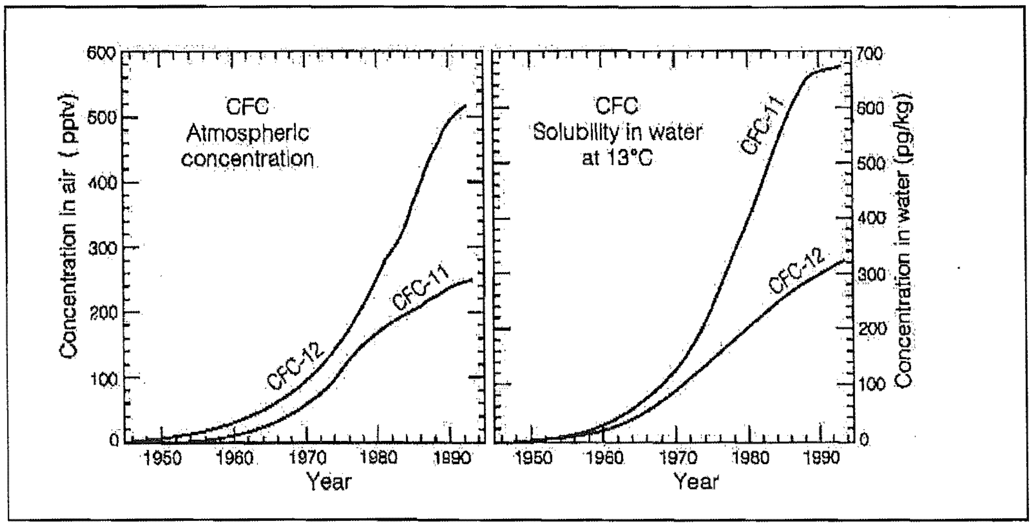



shows that the concentration of tritium did not begin to increase until approximately 1957. The concentration of tritium in Canterbury precipitation is estimated by scaling the average annual values from Kaitoke by a factor of 1.2 (Taylor et al., 1989). While tritium is useful for identifying groundwaters recharged after 1952, determining the recharge year for modern groundwaters (i.e. waters recharged after 1985) is difficult because measured concentrations in the groundwater are again approaching the natural levels in the atmosphere.

### 5.5.1.2 Chlorofluorocarbons (CFCs)

Chlorofluorocarbons (CFCs) are stable organic compounds containing chlorine and fluorine, which are incorporated as dissolved gases in the groundwater molecule from the atmosphere. CFC concentrations in the atmosphere have been increasing steadily because of anthropogenic activity since the 1940s, reaching a peak in the 1990s (Figure 5.14). Because CFCs are extremely resistant to degradation and fractionation, they can be used to date groundwater recharged after 1940 to the present (Thompson and Hayes, 1979). The amount of CFCs present in the groundwater is dependent upon the amount of gas in the atmosphere at the time of recharge and the temperature. The use of both tritium and CFC dating methods enables accurate assessment of the mean residence time, and recharge year (Ekwurzel et al., 1994).

***Figure 5.14 - CFC-11 and CFC-12 concentrations in the atmosphere and water from 1950 – 1995 (Ekwurzel at al., 1994; Clark and Fritz 1997).***




### 5.5.1.3 Oxygen-18 ($^{18}O$)

The naturally occurring stable isotope Oxygen-18 ($^{18}O$) is useful for identifying and mapping groundwater recharge over time (Clark and Fritz, 1997). Measured $^{18}O$ is reported as a $\delta^{18}$ O value, and is an expression of the difference, in parts per thousand, between the isotopic ratio of $^{18}O/^{16}O$ of the sample and the international standard $^{18}O/^{16}O$, the Vienna Standard Mean Ocean Water (V-SMOW) (Clark and Fritz, 1997). Comparison of the measured $^{18}O/^{16}O$ ratio in groundwater and the measured $^{18}O/^{16}O$ ratio in local precipitation provides clues as to the recharge source. The $^{18}O/^{16}O$ isotopic ratio of water varies as it travels through the hydrological cycle as fractionation of the heavier $^{18}O$ and lighter $^{16}O$ molecules occurs with variations in temperature, seasons and altitude. It has been shown that low $\delta^{18}$ O values (- 7.03 to -7.41) in groundwater represent groundwater that has been recharged by local precipitation (i.e. low altitude precipitation), compared to more negative $\delta^{18}O$ values which reflect recharge from higher altitudes, further up in the catchment (Taylor et al., 1989). However, $\delta^{18}O$ values are sensitive to seasonal effects, which influence the altitude in which rain precipitates and the atmospheric temperature, both of which affect the fractionation process. Oxygen-18 methods for identifying recharge sources are more credible after several years of data have been collected in order to establish the local seasonal effects and variations.

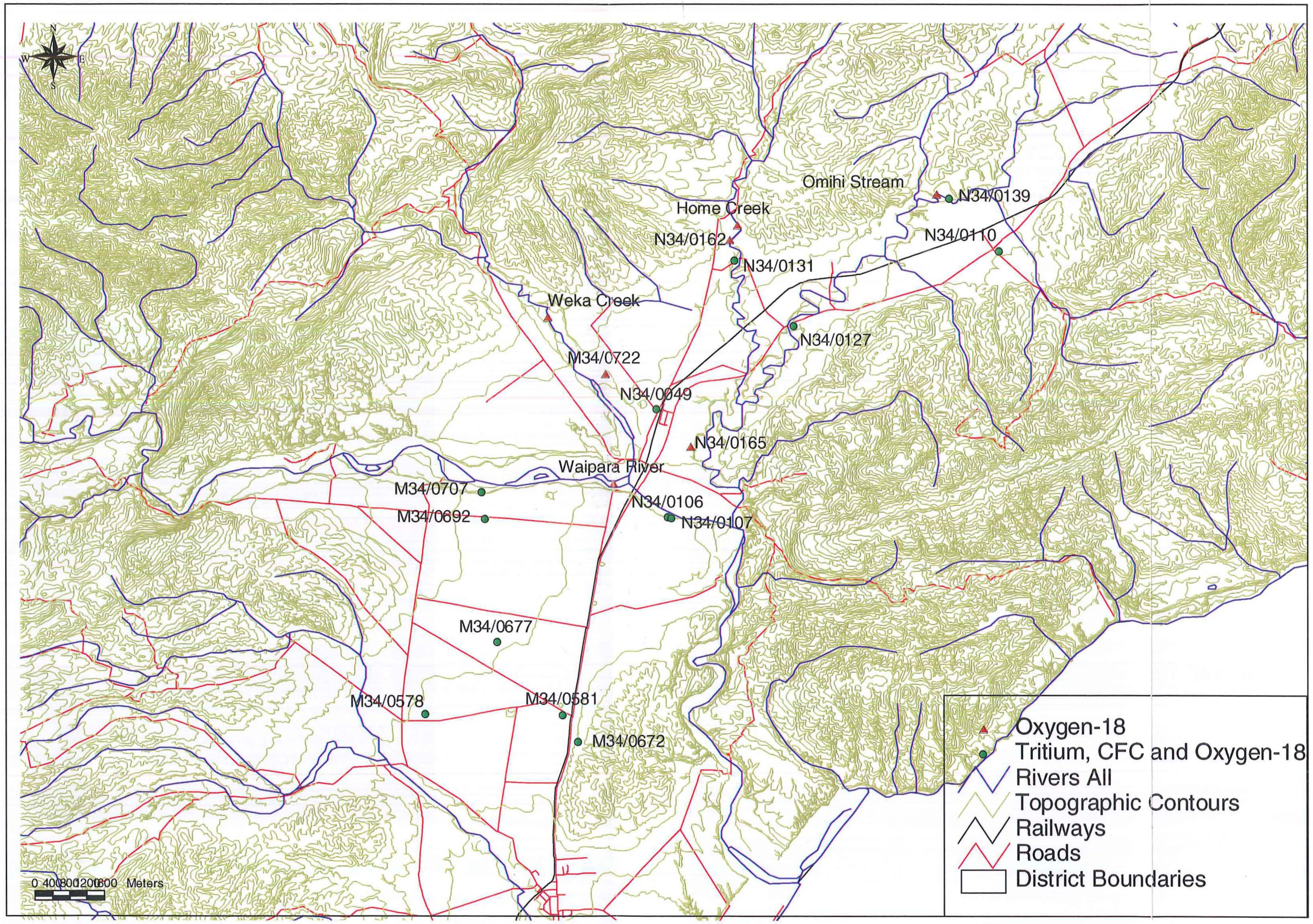
### 5.5.2 Isotope Sampling Programme

A total of 13 wells were sampled for tritium, CFC and oxygen-18 analysis (Figure 5.15). A total of six additional oxygen-18 samples were collected from 1 well, 2 springs, the Home Creek, Weka Stream, and Omihi Stream. Surface waters were sampled to evaluate the interaction between the groundwater and surface waters. Springs were sampled in order to assess their relationship to the groundwater system, and try and identify recharge sources. The number of samples collected and analysed was based on financial limitations. Samples for isotope analyses were collected by the writer and Mike Stewart from the Institute of Geologic and Nuclear Sciences (IGNS).

#### *5.5.2.1 Sampling Methods*

Sampling procedures for all isotopes required the equivalent of three volumes of well water to be purged from the well. Tritium samples were collected in 1 litre plastic bottles, which were flushed twice with the sample water before filling, and capped with a rubber lined metal cap. Oxygen-18 samples were collected in the same manner as

***Figure 5.15 – Isotope Sampling Locations. Wells sampled for tritium, CFCS, and oygen-18 are indicated by green circles, and sites sampled for Oxygen-18 only are shown by red triangles.***



the tritium samples, but collected in glass bottles with a polyseal camp. The sampling method for CFC's is an intricate process, requiring a special apparatus (Figure 5.16) for removing and isolating the sample from atmospheric contamination, which can introduce additional CFCs and distort the results.

### *5.6.2.2 Analytical Methods and Detection Limits*

All samples were analysed at the isotope laboratory at IGNS. The stable isotope $^{18}O$ was analysed by a gas-source mass spectrometer, with a precision range of 1.01 (Dr. M. Stewart, pers.comm., 2000; Taylor at al., 1989). Results are reported in terms of $\delta^{18}O$ activity (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW) concentration. The radioactive isotope, tritium, was analysed by a gas proportional

**Figure 5.16 – Mike Stewart of IGNS torch sealing a CFC sample to prevent atmospheric contamination**

counter and liquid scintillation counter (LSC). Results are reported as tritium units. One unit of tritium (TU) corresponds to one $^{3}H$ atom per $10^{18}$ atoms of hydrogen (Clark and Fritz, 1997). The combined measurement techniques are capable of yielding data with a precision of ±0.8 tritium units (TU). CFCs were analysed by a purge and gas chromatographer with an electron capture detector as described by Busenberg (1992). Errors range from 3% for concentrations greater than 50 pg/l and approach 50% for concentrations at the detection limit (< 1 pg/l), (V. Trompetter, pers.comm., 1999). CFC results are reported as parts per trillion by volume in air that is in equilibrium with the water sample (ppvt or $10^{-12}$).

### 5.5.3 Analytical Results

Analytical results and site details are presented in Table 5.4, and Figure 5.17 shows geographic distribution of the interpreted recharge years from isotopic analyses.

#### *5.5.3.1 Tritium Results*

The recommended recharge years have been calculated using a piston flow model (i.e. no mixing). Measured tritium ratios ranged from $0.006 \pm 0.016$ to $2.01 \pm 0.06$ TR, with the latter showing a significant proportion of post-thermonuclear tritium indicative of modern recharge, and the former representing pre-bomb tritium concentrations, indicating the water was recharged prior to 1940. Most of the samples show the groundwater to have a mean residence time of greater than 50 years. The tritium ratios for all samples, except N34/0049 (34.4 m), N34/0127 (28.0 m), M34/0581 (27.8 m) and M34/0677 (11.8 m), are significantly low and are not distinguishable from zero as they are within the measurement error (Dr. M. Stewart, pers.comm., 2000). The oldest water was sampled from N34/0107 (28.0 m), N34/0131 (75.7 m), N34/0139 (137.0 m) and N34/0110 (48.0 m) demonstrating that groundwater with long residence times is not necessarily contained in the deepest aquifers. Samples N34/0049 (34.4 m) and M34/0677 (11.8 m) have TR values approaching atmospheric levels indicating modern recharge.

#### *5.5.3.2 CFC Results*

Overall, the CFC results are in good agreement with the tritium results. CFC-11 values correlate well with CFC-12 values, except for N34/0127, which shows an excess of CFC-12. An excess of CFC-12 may be indicative of a fraction of younger water recharging the system, or alternatively, the high CFC-12 can be attributed to effects from agricultural chemicals contaminating the water table, which in either case signifies

*Table 5.4 - Well Details and Analystical Results for Tritium, CFC and Oxygen-18 Sampling (1999 - 2000)*

| CRC Well Number | Site ID | Sample Date | Grid Reference | Well Depth (m) | Comments | $^{18}O$ ‰ | CFC-11 | | CFC-12 | | Recommended Recharge Year | Tritium Ratio (TU) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Average pptv | Model Year | Average pptv | Model Year | | |
| N34/0106 | CRC304109 | 23-Apr-99 | N34:9064-9228 | 68.2 | Artesian | -8.49 | 0.0 | <1940 | 0.0 | <1940 | pre-1940 | 0.006 ± 0.016 |
| N34/0107 | CRC304158 | 23-Apr-99 | N34:9064-9228 | 28.0 | Artesian | -8.57 | 0.4 | <1960 | 2.8 | 1945 | 1945 | 0.027 ± 0.017 |
| M34/0707 | CRC304167 | 23-Apr-99 | M34:8658-9287 | 30.0 | | -8.2 | 2.7 | 1954 | 17.6 | 1955 | 1955 | 0.039 ± 0.019 |
| M34/0578 | CRC304131 | 23-Apr-99 | M34:8505-8778 | 66.0 | | -8.69 | 1.4 | 1952 | 20.8 | 1956 | 1956 | 0.012 ± 0.017 |
| N34/0127 | CRC304112 | 24-Apr-99 | N34:9064-9352 | 24.0 | Artesian | **-7.85** | 2.0 | 1953 | 1628 | Excess | Excess | 0.930 ± 0.033 |
| M34/0672 | CRC304095 | 24-Apr-99 | M34:8855-8714 | 35.7 | | -8.48 | 3.8 | 1955 | 9.0 | 1952 | 1952 | 0.015 ± 0.017 |
| M34/0581 | CRC304090 | 24-Apr-99 | M34:8818-8876 | 27.8 | | -8.39 | 35.7 | 1968 | 253.1 | 1978 | 1968 | 0.041 ± 0.018 |
| Waipara River | | 24-Apr-99 | M34:8932-9328 | | $^{18}O$ only | -8.44 | | | | | | |
| M34/0692 | CRC304100 | 19-Feb-00 | M34:8642-9225 | 27.8 | | -8.45 | 5.0 | 1957 | 39.0 | 1962 | 1962 | 0.241 ± 0.023 |
| N34/0110 | CRC304110 | 19-Feb-00 | N34:98237-98370 | 48.0 | | **-7.61** | 8.0 | 1960 | 62.0 | 1965 | pre-1940 | 0.024 ± 0.023 |
| N34/0139 | CRC304115 | 19-Feb-00 | N34:97105-99564 | 137.0 | Artesian | -8.70 | 4.3 | 1956 | 14.0 | 1955 | pre-1940 | 0.030 ± 0.018 |
| N34/0131 | CRC304113 | 19-Feb-00 | N34:92174-98141 | 75.7 | Artesian | -8.31 | 0.0 | <1949 | 0.0 | <1940 | pre-1940 | 0.029 ± 0.023 |
| N34/0049 | CRC304157 | 19-Feb-00 | N34:90377-94732 | 34.4 | | **-7.74** | 59.5 | 1971 | 241.5 | 1978 | 1978 | 1.99 ± 0.06 |
| M34/0677 | CRC304164 | 19-Feb-00 | M34:86691-89427 | 11.8 | | -8.47 | 172.3 | 1982 | 423.3 | 1988 | 1988 | 2.01 ± 0.06 |
| M34/0722 | CRC304156 | 24-Feb-00 | M34:89176-95538 | 66.0 | $^{18}O$ only | **-7.93** | | | | | | |
| N34/0162 | CRC304163 | 22-Feb-00 | M34:87945-96751 | spr | $^{18}O$ only | -8.25 | | | | | | |
| N34/0165 | | 24-Feb-00 | M34:91230-93799 | spr | $^{18}O$ only | -8.27 | | | | | | |
| Waipara River | | 21-Feb-00 | M34:8932-9328 | | $^{18}O$ only | **-7.68** | | | | | | |
| Home Creek | | 19-Feb-00 | N34:92180-98850 | | $^{18}O$ only | -8.20 | | | | | | |
| Weka Creek | | 19-Feb-00 | N34:92051-98624 | | $^{18}O$ only | **-7.38** | | | | | | |
| Omihi Stream | | 02-Oct-99 | M34:96777-99568 | | $^{18}O$ only | **-7.16** | | | | | | |

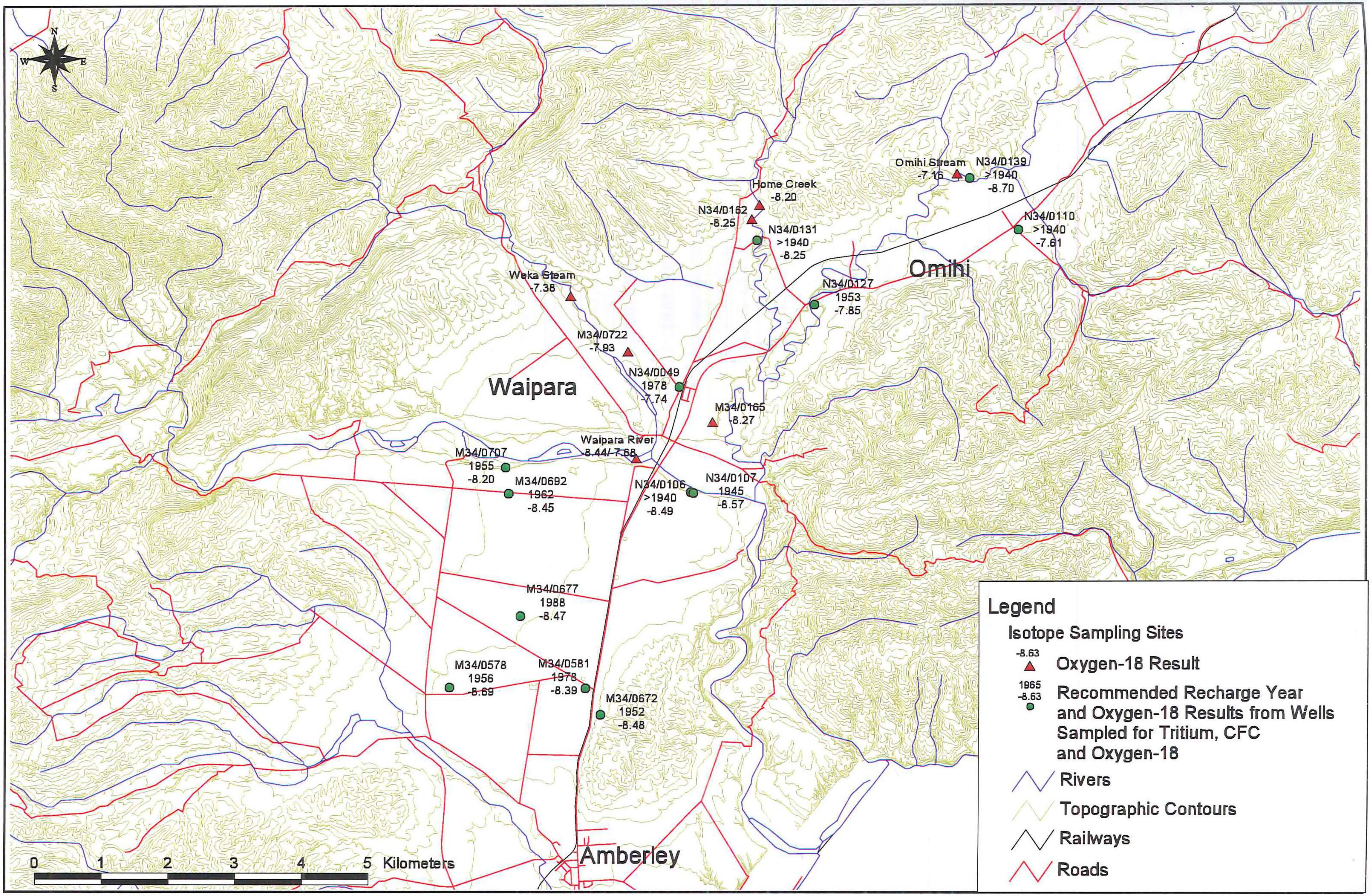
**Units:**

CFC concentrations are given in parts per trillion by volume in air in equilibrium with the water sample (pptv or 10 to the power of -12).

The tritium concentrations are in Tritium Ratios (TR = 1 signifies a tritium/hydrogen ratio of 10 to the power of -18).

Oxygen-18 concentrations are given as δ values, where $\delta^{18}O$ in ‰ = $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1] \times 1000$. The standard is Standard Mean Ocean Water (SMOW)

*Figure 5.17 - Geographic Distribution of Recommended Recharge Years and Oxygen-18 Concentrations*



the input of modern water. The CFC-11 suggests that the sampled groundwater contains a mixture of both old water with long residence time, and young water, possible derived from surface infiltration of local precipitation. However, CFC-11 can be affected by degradation processes in the unsaturated zone, and therefore, recommended recharge years tend to be conservative. A recharge year has been determined for sample N34/0127. CFC-11 and CFC-12 were not detected in samples N34/0131 and N34/0106, correlating well with the tritium results therefore, providing further evidence that recharge occurred long before 1940. . Based on the reported tritium values, a residence time of 80 years has been suggested by Dr. Stewart (pers.comm., 2000). Samples N34/0107 (28.0 m), M34/0707 (30.0 m), M34/0578 (66.0 m) and M34/0672 (35.7 m) all have low CFC concentrations and low TR values indicating that they were recharged prior to 1960. CFC-11 results show the groundwater to be old, except M34/0581, N34/0049, and M34/0677. CFC results from N34/0581 indicate a fraction of modern groundwater is present, and the low tritium values strongly suggest that dispersion is occurring. M34/0677 (11.8 metres) is most likely recharged by surface infiltration or by river recharge. However, the well is not accessible for water level measurements, and comparison of water level fluctuation with river level fluctuations cannot be assessed. Based on results from the river gaugings (Chapter Four), the groundwater chemistry, it is concluded that the well is being recharged from local precipitation. N34/0049 (34.4 m) shows relatively high CFC-11 and CFC-12 concentrations compared to the other samples. The CFC results are in good agreement with the measured tritium values. The recommended recharge year is 1978. The well is located in the Waipara township, northeast of the Weka Creek and southeast from the Glenmark Irrigation scheme, and the relatively young groundwater is believed to be derived from either leakage from the Glenmark Irrigation Scheme storage facilities, or recharge from the Weka Creek.

#### *5.5.3.3 Oxygen-18 Results*

Figure 5.18 shows distribution of measured oxygen-18 values. Samples for oxygen-18 analysis were collected from wells, springs and surface water. Oxygen-18 values range from –7.16 to –8.69 ‰, with the more negative values (-8.69) interpreted to represent high altitude recharge, and the more positive values (-7.16) $\delta^{18}O$ represent low altitude recharge. Initial examination of Figure 5.20 shows that the more positive oxygen-18 values are located north of the Waipara River, with the exception of the February 2000 sample of the Waipara River, which had an $\delta^{18}O$ value of –7.68 ‰. The more positive $\delta^{18}O$ value sampled in February illustrates the seasonal variation associated with the change in climate and precipitation patterns. The surface waters exhibited more negative $\delta^{18}O$ values which suggest that summer recharge in the catchment occurs from local, low altitude precipitation. The Home Creek $\delta^{18}O$ value exhibits a more negative value indicating that recharge is derived from high altitude precipitation, and a different recharge source than the other surface waters. The region in which the sample was collected is an area that is particularly saturated with water all year round, and spring N34/0162 is an example of this. The high value may indicate that the Creek may be recharged from the groundwater. Given the close $\delta^{18}O$ values for N34/0162 and the creek, it is suspect that the two are recharged from the same source.

Groundwater $\delta^{18}O$ values range from –7.61 to -8.70‰, indicating that the source of recharge is most likely a mixture of local and high-altitude precipitation typical of higher up in the catchment. The regional differences most likely reflect different recharge sources. However, it is difficult to it assess whether the $\delta^{18}O$ values are the result of seasonal effects or are they indicative of the recharge source. Sample M34/0677 shows a similar $\delta^{18}O$ value to the Waipara River (April 1999 sample), suggesting that it may be recharged from the river during the winter months. Samples from N34/0162 (Gould Spring), N34/0165 (Harris Spring) and Home Creek all have similar $\delta^{18}O$ values, which suggest that they are recharged from the same region.

## 5.6 Chapter Summary

Chemical sampling and analysis of thirty-eight wells located in various parts of the basin show that groundwaters of the Waipara basin are of three types: calcium carbonate type, sodium carbonate type and a "non-dominant" type. The majority of the sampled groundwaters represent the non-dominant type and are located within the central and southern parts of the basin. Sodium type groundwaters appear to occur randomly throughout the basin at a variety of different depths. Calcium type waters occur primarily in the northern part of the basin (except for M34/0707 and M34/0754) and is indicative that most of the groundwater in the northern part of the valley is being recharged from water flowing through the Tertiary hills along the eastern and western margins of the basin. The predominance of non-dominant type waters in the central and southern part of the basin suggests that mixing of groundwaters derived from different sources is occurring. Potentiometric surface data combined with groundwater chemistry data strongly supports this hypothesis.

The long residence times of the Waipara groundwaters is attributed to percolation of local precipitation through fractures, joints and sinkholes formed in the Tertiary sequences located along the margins of the basin. In addition, direct infiltration of rainfall and surface runoff into the unconfined zone, or semi-confined zone results in long residence times because of the low transmissivity, storativity and hydraulic conductivity of the aquifers, which retard both vertical movement and lateral flow of the groundwater. In addition, the existence of low permeability boundaries and barrier boundaries ultimate affects the flow paths, and movement of groundwater through both the unsaturated and saturated zones.

Chemical analyses and interpreted residence times from isotope data provides evidence that groundwater recharge is occurring from downward percolation of local precipitation as indicated by CFC and tritium concentrations measured from N34/0127, N34/0049, M34/0677 and M34/0581 samples. The overwhelming number of samples exhibiting residence times of greater than 30 years indicates that the movement of groundwater through the system is extremely slow. In addition, the samples that are interpreted to have residence time greater than 40 years may indicate that portions of the groundwater resources of the Waipara region are limited, and requires careful monitoring to determine whether they are finite or sustainable resources. The long-term sustainability ultimately depends on the acknowledgement of the limitations of the resources (i.e. total availability versus total volume allocated).

# CHAPTER SIX
# SUMMARY, CONCLUSIONS and RECOMMENDATIONS FOR FUTURE WORK and RESOURCE MANAGEMENT

## 6.1 Thesis Summary

The main objective of this investigation was to provide a comprehensive evaluation of the groundwater resources in the region, and to generate a conceptual model of the groundwater system(s). Consequent objectives include: collation of information about the groundwater resources of the Waipara Basin, identification of the hydrogeological properties of the aquifers and sources of groundwater recharge, development of a long-term monitoring programme, and to suggest future investigation strategies for effective management of the groundwater resources.

### 6.1.1 Geology

The geology of the Waipara Basin consists of Torlesse Tertiary basement, marine transgression formed sandstone, limestone and mudstone sequences, which were later folded and faulted as a result of the development of the convergent plate boundary and the beginning of the Kaikoura Orogeny. Uplift and erosion of the Southern Alps during the Kaikoura Orogeny produced thick accumulations of Early Pleistocene fluvial deposits, the Kowai Gravels. Accelerated erosion of topographic highs due to increased tectonic activity and climatic fluctuations in the Quaternary resulted in infilling of the Waipara Basin with a massive quantity of gravels. Late Quaternary deposits, the Teviotdale and Canterbury Gravels, were formed during glacial and interglacial periods resulting from several cycles of aggradation and degradation. Aggradation of alluvial deposits by the ancestral Waipara River controlled the base level of the northern basin ancestral rivers and major tributaries resulting in the deposition of sediments that were lithologically distinct from the material in the southern part of the basin. The Canterbury and Teviotdale gravel deposits of the northern part of the basin are referred to as the omihi gravels, and the time-equivalent gravels infilling the central and southern part of the basin are referred to as the waipara gravels.

Subsurface geologic structures associated with the active tectonic regime influenced the depositional and erosional history of the basin by forcing rivers to change their channel morphology from braided to meandering in response to uplift and deformation. Fluctuations in climate and sea levels were instrumental in forcing the rivers and streams to alter their courses, resulting in cycles of cut and fill associated with periods degradtion and aggredation. The changing depositional environment prevented the development of laterally continuous, well-sorted, permeable aquifers. The hydrogeology of the Waipara Basin consists of aquifers resulting from numerous cut and fill cycles formed during periods of aggradation and degradation of the land surface forming discrete buried more permeable paths of flow, and semi-permeable lenses that are geologically heterogeneous and of variable thickness.

Surveys of geomorphic features of the basin have resulted in identification of the Amberley structure, a ENE trending 1-2 metre rise in the land surface. The exact nature of the structural feature has not been determined at present and requires further investigation. To the north of the structure, on the downthrown side, a swamp has formed, providing evidence that structural features have an effect on the formation and distribution of hydrogeological features. In addition, the swamp formed to the south of the structure, is most likely affected by both the propagating Cass Anticline and the Amberley structure. How the deeper aquifers are affected has yet to be determined, and recently drilled wells on the south side of the structure may provide these answers.

### 6.1.2 Geophysics

Gravity surveys carried out have defined depth to basin in the northern part of the basin and in the central part of the basin along Georges Road. Modelling and interpretation of gravity data from the Glenrose-Spye survey suggest gravel thicknesses to range from 300 – 400 metres, with a minimum thickness of 150 metres located at the hinge of a fault propagated fold. The survey was unsuccessful in constraining the location of the Omihi Fault. Modelling and interpretation of the Georges Road gravity survey data suggest that gravel thicknesses increase in the central part of the basin. Cover deposit thicknesses range from 900 to 300 metres. Basement topography is undulating and disrupted with faulting at depth. An example of such a structure is the fault reverse thrust fault associated with The Mound.

Time-domain electromagnetic (TEM) surveys were unsuccessful in identifying and mapping aquifers and water-bearing units because the electrical properties of the water-bearing units and surrounding subsurface medium are too similar, and therefore the TEM methods cannot resolve the water-bearing units. Both the confining layers and aquifer units are composed of conductive clays and silts which trap the signal and prevent the signal from reaching depth of penetration greater than 100 metres. TEM methods were able to identify geo-electrical boundaries as shown in Figure 3.18 and 3.19; however, the interpretation of the nature of those boundaries is poorly constrained.

TEM surveys were successful in differentiating geologic regimes by comparing the geo-electrical properties of the soundings. Survey showed that the depth of penetration was limited for the soundings carried out in the northern part of the basin because the relatively conductive nature of the gravel deposits. The conductive nature of the deposits is best explained by the influence of the limestone, which by itself is not a conductive medium but when it interacts with waters, the ionic content is increased, thereby resulting in an increase in conductivity. Survey carried out in the southern part of the basin, show the depth of penetration to be greater, and the transmitting medium to be more resistive than the deposits in the northern part of the basin.

Overall, TEM methods are not appropriate methods for groundwater exploration within the Waipara basin. The most appropriate geophysical method may be seismic surveys, which are capable of penetrating greater depths with better resolution. However, the acoustic properties of the material again, need to be sufficiently different. Presently, tests are being carried out in the Omihi area to evaluate the merits of using seismic methods to define aquifers and basement structure.

### *6.1.3 Hydrogeology*

#### 6.1.3.1 Aquifer Identification and Delineation

Aquifers presently being utilised are included in the Canterbury (Waipara and Omihi gravels), Teviotdale Gravels, and the Kowai Gravels. Aquifers are confined, and cannot be readily distinguished by characteristic hydrogeologic confining or semi-congfining units. Aquifers occurring in the Canterbury and Teviotdale aquifers cannot be differentiated in terms of stratigraphy, lithology, and hydrogeological properties, and therefore the aquifers occurring within them are grouped as the Canterbury-Teviotdale Aquifers (CTA). The aquifers formed in the Kowai Gravels (KGA) can be distinguished from the CTA by their hydrogeologic properties (i.e. sediment composition, yield, transmissivity and groundwater chemistry), and are designated undifferentiated KGA. The KGA are composed of larger more rounded gravels derived from the Torlesse Supergroup. KGA yields are considerably higher because fine sediments consist of predominantly sands and silt, with a smaller proportion of clay than exhibited by the CTA. There are approximately 11 wells that penetrate the KGA (N34/0139, N34/0134, N34/0142, N34/0143, N34/0126, N34/0131, N34/0138, N34/0145, M34/0726, N34/0106, and are the best yielding wells in the basin. However, all wells are screened over several water-bearing units with individual yields of approximately 2 l/s. Table 6.1 summarises the hydrogeologic properties of the CTA and KGA. Note that the properties of the omihi and waipara gravels are listed and described.

#### 6.1.3.2 Aquifer Tests

Aquifer tests were carried out for two wells penetrating the CTA (M34/0689 and M34/0659) and one penetrating the KGA. All aquifer test time-drawdown data showed the presence of boundary conditions associated with an impermeable boundary or a low-transmissivity boundary, and provides further support for the suggested conceptual model. Aquifer tests show that the transmissivity and storativity of the CTA are low, and recharge is slow, and is expected where boundary conditions exist, which is a reflection of the past depositional enviornment, and nature of the sedimentology. The aquifer test carried out for N34/0143 (KGA) shows the transmissivity to be greater, but calculated storativity and hydraulic conductivity values are comparable to the values from the CTA

**Table 6.1 – Summary of Hydrogeologic Properties of the Aquifers in the Waipara Alluvial Basin.**

| **Formation Aquifers** | **Depth Range (mbgl)** | | **Yield[1] (l/s)** | **Transmissivity ($m^2$/day)** | **Storativity (dimensionless)** | **Hydraulic Conductivity (m/day)** | **Lithologic Description* Showing Regional Variations** | | **Chemical Signature** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **South Waipara** | **North Waipara and Omihi** | | | | | *waipara Gravels* | *omihi gravels* | South Waipara | Waipara and Omihi |
| Recent Deposits | flood plains adjacent to modern day stream courses | | 2 – 22 | undetermined | | | Large boulders and gravels composed predominantly of greywacke; some Tertiary Limestones and Sandstone with silt and clay | Large boulders and gravels composed predominantly of Tertiary derived clasts with calcareous silts | undetermined | |
| Undifferentiated Canterbury Gravel Aquifers (CTA) | 2 – 50 | | .2 – 3.0 | 17 | .0005 .0001 | 4 | Greywacke gravels claywashed and claybound brown-grey silt and clay matrix; | Greywacke claywashed and claybound gravels with brown-silt and clay; | Sodium Bicarbonate and no dominant Type | Calcium Bicarbonate and no dominant type |
| Undifferentiated Teviotdale Gravel Aquifers (CTA) | | | | | | | Weathered greywacke gravels increase in Tertiary derived clasts with depth; yellow-brown silty clay; | Weathered clasts predominantly derived from Tertiary formations with yellow-brown silty clay; | | |
| Undifferentiated Kowai Gravel Aquifers, including Lower Kowai/Greta Beds* (KGA) | > 100 (?) | > 50 | 8 -18[3] | 78 | .0003 | 6 | Large rounded, weathered gravels, composed of predominantly of Torlesse derived clasts, often with iron staining, and higher proportion of sand than silt; Proportion off limestone derived gravels decreases with depth; occurrence of shells indicative of transition from Kowai to Lower Kowai (Greta Beds); | | Calcium bicarbonate? | Calcium Bicarbonate and Sodium Type |

[1] Listed yields reflect the cumulative yield of several water-bearing units as reported by driller as the yields of individual water-bearing units are generally not recorded during drilling
[2] Aquifer lithologies will vary as a result of localised influences in the depositional history and catchment source
[3] Highest yielding well at time of writing (N34/0131)

tests. This is significant because it suggests that the higher yield and transmissivity of the KGA, is a function of aquifer thickness rather than actual aquifer permeability. The Broomfield-aquifer test was particularly successful in demonstrating the hydrogeological variability as the drawdowns in the observation wells were extremely variable. In addition, well M34/0666 was located approximately 250 metres from the pumping well and failed to respond to pumping, whereas wells M34/0661 and M34/0662, located approximately 350 metres away, responded by exhibiting over a metre drawdown. The test demonstrates the problem of evaluating which wells are hydraulically connected based on stratigraphic information alone, and shows that the only way to evaluate potential adverse effects in this hydrogeologic environmnet is to conduct long-term constant discharge tests over a period of 24 hours or more.

#### *6.1.3.3* *Potentiometric Surface and Groundwater Flow Direction*

Potentiometric surveys carried were not successful in defining a regional potentiometric surface. Complications in establishing a regional surface is due to the fact that wells are screened over several water-bearing units, each exhibiting individual aquifer pressure heads, and therefore the resultant pressure head represents a cumulative head. In addition, the depositional and structural nature of the deposits as depicted in the schematic illustration of the relationship of the hydrogeological features of the basin (Figure 4.28, back pocket), makes it difficult to determine which wells are hydraulically connected, as wells of similar depths may not necessarily be penetrating the same aquifer. Potentiometric surveys show the overall regional groundwater flow direction to be to the south-southwest in Omihi (estimated) and Glenmark, and to the south-southeast in Waipara and Glasnevin area. The hydraulic gradient small and groundwater movement is slow.

#### *6.1.3.4* *Groundwater Fluctuations*

Monitoring of long-tem aquifer fluctuations cannot be established at present as only one year of data has been collected. Observed fluctuations are attributed primarily to seasonal responses to rainfall and to barometric effects. Recharge events associated with increased rainfall and decrease evapotransipration into the system were observed between July and September, and again in the autumn during Feb-March. From

September to February, water-levels tend to steadily decrease, with a sharp decline observed at the end of February/March which is attributed to pumping. The 1999/2000 summer was climatically unusual with greater than average amounts of rainfall and north-easterly winds, which resulted in a delay of the start of the irrigation season until February, as opposed to the usual December start.

Fluctuations associated with daily rainfall and stream level fluctuations have not been observed.

*6.1.3.5 Surface - Groundwater Interactions*

Gaugings and analysis of existing data suggest that the Home Creek, Omihi Stream and Waipara River are gaining rivers and streams. Assessment of actual gains from the groundwater resource is difficult as data records are incomplete. A lack of data for the Weka Creek prevents evaluation of groundwater-stream interaction. Isotope data from N34/0049 shows that groundwater is relatively young with a recharge year in 1978, and suggests that the groundwater may be recharged from the Weka Creek, or from leakage downward into the deeper aquifers from the Glenmark Irrigation storage ponds.

### 6.1.4 Groundwater Chemistry

*6.1.4.1 Groundwater Chemistry*

Results of chemical analyses from selected wells in the Omihi area show that the source of recharge and chemical signature of the aquifers is distinct from the chemical signature of sampled aquifers located in the central and southern part of the basin. Omihi samples are enriched in calcium bicarbonate, total dissolved solids and the groundwater characterised as hard water, all of which indicate that the most likely source of recharge is the limestone hills located along the eastern and western margin of the basin. Further support of limestone recharge comes from well N34/0110, which was pumped dry during 2000 irrigation season, and water level observations since then have recorded the recovery of the well, which took 2-3 months (Appendix D-10). Long recovery periods on the order of months are typical in fractured bedrock hydrogeologic regimes. In addition, the groundwater chemistry and the suggested residence time from isotope sampling (> 50 years) provides further evidence that the aquifer is being recharged from the limestone. The observed hydrogeological characteristics indicate that the primary source of recharge for Omihi groundwaters, both shallow and deep aquifers, is the limestone hill/Tertiary rock that confine the alluvial basin.

South of Omihi, the sampled aquifers consist of softer water that is not as high in calcium or TDS. It is believed that groundwater flow originates from both the north-north east and north-western margins of the basin (Figure 4.7), and the aquifers in the central margin of the basin may represent a zone of mixing between groundwater recharging from the northern part of the basin, and local precipitation infiltrating unconfined regions of the aquifers. Evidence for a mixing zone comes from the abundance of groundwaters characterised as "non-dominant type," in which sodium and calcium are present in almost equal proportions.

Chemical sampling was completed for a variety of aquifers at variable depths, and results show that that the Omihi region has a distinct chemical signature from the rest of the basin samples.

#### *6.1.4.2 Isotope Analyses*

Results from tritium, CFC and oxygen-18 sampling show the groundwater to have long-residence times and is explained by the lack of direct local recharge into the aquifers (except for M34/0677, M34/0581 and N34/0049), and the low permeability and hydraulic conductivity of the aquifers. Aquifers located south of the Waipara River are suspected to be recharged primarily from local precipitation infiltrating the unconfined portion of the aquifers. Based on groundwater flow directions, aquifers in the south may also be recharging from Omihi.

Isotope sampling results for wells N34/0106, N34/0110, N34/0139 and N34/131 all show recharge years prior to 1940, and is an issue of great concern because of the potential that continued and unmonitored groundwater abstraction may lead to deletion of the resource.

Oxygen-18sampling results proved to unsuccessful for defining recharge sources.

Before oxygen-18 data can be applied for groundwater studies in the Waipara basin, periodic sampling needs to be undertaken to establish seasonal variations.

## 6.2 Recommendations for Future Monitoring and Management

The recommendations are made for further work to help better characterise, and manage the Waipara resources to ensure sustainability. The isotope results show that there is a potential that the resource is limited and there is the potential that extraction of the groundwater at a reate faster than recharge is occurring will resullt in the mining of the resource. In order to evaluate the sustainability of the groundwater resources, recommended further work includes groundwater monitoring of water levels to evaluate cumulative effects; completion of further aquifer tests to evaluate the adverse effects associated with groundwater abstraction, and development of management strategies that help to both increase the knowledge of the resource, and protect it at the same time.

### 6.2.1 Resource Monitoring

In order to determine cumulative effects of groundwater abstraction to ensure that the groundwater resources are sustainable and not being depleted at a rate faster than it is being recharged, monitoring of aquifer water-levels is essential. This is vital given the number of bore permits and applications for groundwater abstractions that have been and will be received in the coming year as the Waipara region continues to expand and develop. Effective management and preservation of the groundwater resource is dependent upon an active water level monitoring program that is continued for at least 5 to 10 years. In conjunction with monitoring of water-levels, records of abstraction rates by well owners should be a required condition placed on consents ofr groundwater abstractions, in order to aid in the monitoring of usage, and in the nterpretation of water-level monitoring data.

Carbon or silicon isotope sampling of N34/0107, N34/0139, N34/0131 and N34/0110 to determine the exact recharge year of the groundwater to ensure that the groundwater is not connate (formation) water and is being recharged. If the water is actively being recharged, then careful management of groundwater is vital for ensuring that the resource is recharging at a rate comparable to the extraction rate. In order to do so, an estimate of the rate of recharge, total abstraction rates, and total storage of the hydrogeologic system(s) is required. Therefore, monitoring of water levels, quantification of groundwater usage through water meter monitoring, and completion of a water balance model for the hydrogeologic regimes are necessary.

### *6.2.2 Adverse Effects of Groundwater Abstractions*

Aquifer tests carried out in three locations were all terminated before 24 hours of pumping, as the drawdown never reached a steady state, a condition that is common where hydrogeological boundaries exist. Analysis of aquifer test data shows that impermeable or low transmissivity boundaries were encountered during all three tests. Calculated transmissivity values are extremely low as shown in Table 6.1, and reflect the poorly sorted nature of the deposits. Based on the findings in the pump tests, Waipara hydrogeological conditions are characterised as heterogeneous, anisotropic water-bearing units. Because of the heterogeneous nature, it is difficult to predict which observation wells (or neighbouring wells) will be affected the most by pumping by simple examination of stratigraphic logs. Long-duration aquifer tests are the *only* way to positively determine the adverse affects of pumping on neighbouring wells, and demonstrated in Chapter Four, and are vital for understanding the spatial geometry and hydraulic limits of the Waipara aquifer system(s).

In addition, in order to evaluate the total available storage of the hydrogeological system(s), evaluation and quantification of individual components of the the water budget needs to be defined. However, based on the hydrogeologic heterogeneity of the aquifers as demonstrated by this study, defining the total storage of the groundwater system will undoubtedly require the application of a vast number of assumptions for defining the physical geometry (i.e. areal extent and volume) of the aquifers. Carrying out additional aquifer tests will help to better delineate the spatial limits of individual aquifers. It has been demonstrated that it is difficult to establish whether wells are hydraullically connected from well depth, bore logs and chemical data, and that the best way to determine if wells are hydraulically connected is through aquifer tests. In addition, the variability of aquifer thickness, permeability, and transmissivity results in anisotropic hydraulic conditions which are represented by the relative drawdowns of the observation wells. It has been shown that wells located in close proximity to one another, may not be hydraullically connected, and that wells located greater distances from the pumping well exhibit a greater drawdown than wells located closer to the pumping well. The physical and hydraulic properties of the Waipara aquifer system require aquifer tests to be completed in order to accurately determine the degree of the hydraulic connection and adverse affects associated with pumping. Based on the previous discussion, the following management strategies are recommended:

- <u>Consent to Drill a Groundwater Bore</u>
  When granting a consent to drill a bore, it should be required that for wells that are screened over multiple aquifers, the owner is required to provide information about each of the penetrated/utilised aquifers. Information that should be collected by the driller includes: initial water level, lithologic sample, and chemical sample analysing for the major cations and anions listed in Chapter Five. This will require the driller to properly develop each aquifer penetrated, and provide information regarding the safe yield and total drawdown. This procedure will help to better identify and monitor utilised aquifers. At present there is no information about individual aquifers for multi-screened wells. Without information and knowledge about the individual aquifers being utilised, effective and sustainable management will be impossible.

- <u>Groundwater Abstraction Consents</u>
  Implementation of a special condition for groundwater abstraction consents in the Waipara basin. The condition should require residents to conduct a constant discharge aquifer test with several observation bores, for wells located within a 700 metre radius of one another. In addition, the aniostropic nature of the aquifer system results in different total drawdown responses in wells, so while pumping of a well may result in a five metre drawdown in one neighboring well, it may not produce any adverse effects in another. For both the protection of exisiting residents and new residents wanting to develop the land for horticulture, determination of adverse effects is imperative for responsible use of the resource.

- <u>Groundwater Abstraction Consents: Domestic Use versus Horticultual Use</u>
  Normally, consents for groundwater abstractions under 20,000 l/day are included in the domestic usage category. However, observations during the past year show that many land holders who have domestic take permits are actually using the bores to irrigate horticulture crops. While the total groundwater take is comprable for horticultural crop irrigation and domestic usage, the way in which the aquifer resource is used is quite different, and adverse affects have been observed in neighboring wells.

  Domestic usage normally results in the aquifer being pumped for several minutes to hours, several times a day, allowing for continual recharge during periods when the well is not being used. With horticultural usage, the aquifer is pumped hours at a time to refill 25,000 litre storage tanks, which results in a large cone of depression, spreading over a wide radius causing noticable drawdown in neighboring wells. Based on the observations, it is suggested that those persons intending to use the wells for horticultual irrigation, even though the total amount of groundwater abstraction is the same, are required to apply for a irrigation abstraction consent rather than a domestic one. This will enable careful monitoring of abstraction rates, and protect the development and resource requirements of the well owner.

- <u>Encouragement of bore owners to manage and protect their resource</u> by encouraging them to maintain records (i.e. water meters) of abstraction quantities and rates, which are useful for evaluating total groundwater abstraction (particularly important for wells used for irrigation and areas of high concentration), and depletion over time.

### *6.2.3 <u>Other Recommendations for Future Work</u>*

Other important steps for proper monitoring and management of the resources of the Waipara alluvial basin include:

1) Drilling of a monitoring bore(s), with proper logging of lithology, aquifer yield, and comprehensive investigation of all aquifers penetrated, which will help to identify

approximately how many aquifers are being utilised, which is a concern for multi-screened wells. Complications in resource management exist because of the fact that wells tend to be screened over several units. How can a resource be effectively managed when the number of utilised resources are not known? In order to better identify and manage resources it should be required that all aquifers be developed and tested during the drilling process.

2) Stream gauging of the Omihi, Weka and Home Creeks to evaluate groundwater-Surface-groundwater interactions, is vital for evaluating the total water balance of the basin. Present gauging data is incomplete and insufficient.

Carrying out the above monitoring programmes and management strategies are the only means to protect the groundwater resource, and to ensure future sustainable development. Proper management strategies, along with monitoring will effectively prevent "mining", and help to sustain the groundwater resources. It has been demonstrated that the Waipara alluvial basin contains groundwater resources capable of promoting horticultural development, however, in spite of the availability, the development of the resource may be limited. Development of a groundwater resource in which the usage is greater than the rate of recharge, effectively results in "mining". The availability of the resource is dependent upon the long term balancing of the rate of extraction and the rate of recharge. Because the rate of recharge is controlled by natual influences such as seasonal and annual rainfall, evaporation, etc., the only way to ensure sustainability of the groundwater resources is to monitor and manage the rate of abstraction. Effective management can only happen with sufficient knowledge of the resource in terms of availabilty and/or limitations, and this information has yet to be established.

# REFERENCES


Andrews, P.B. 1963: Stratigraphic Nomenclature of the Omihi and Waikari Formations, North Canterbury New *Zealand Journal of Geology and Geophysics 6(2)*: 228-255

Barnes, P.M. 1994:Structural styles and sedimentation at the southern termination of the Hikurangi subduction zone, offshore North Canterbury, New Zealand. PhD thesis, University of Canterbury Library, Christchurch, New Zealand.

Beeching, A. Ryan, G. 1999: Field Geophysical Investigation of the Depth to Basement Below Georges Road, Waipara, Canterbury, New Zealand. Unpublished Environmental and Engineering Geophysics (ENGE 467) project report; Department of Geological Sciences, University of Canterbury, 1999.

Begemann, F. Libby, W.F. 1957: Continental water balance, ground water inventory and storage times, surface ocean mixing rated and world-wide circulation patterns from cosmic-ray and bomb tritium. *Geochimica et Cosmochimica Acta 12*: 277-296.

Bevin, A. J. 1991: M34 Amberley (Limited Revision) Topographic Map 260, 1: 50 000. Land Information New Zealand, Wellington New Zealand.

Bradshaw, J.D. 1975: The folds at Castle Hill (Canterbury) and their bearing on Kaikouran deformation style in the Canterbury Basin. *Journal of Royal Society of New Zealand 5*: 209 – 217.

Brooks, T. 1997: *Aquifer test near Te Pirita.* Canterbury Regional Council Unpublished report U97/41, Christchurch.

Brown, L. J. Weeber, J.H. 1982: Water wells between the Ashley and Waipara Rivers, *New Zealand Geological Survey Bulletin* 81.

Brown, L.J. Wilson, D.D. 1988: Stratigraphy of the Late Quaternary deposits of the northern Canterbury Plains, New Zealand, *New Zealand Journal of Geology and Geophysics 31*: 305-335

Brown, L. J. 1998: *Bexley Groundwater Testbore Results,* Canterbury Regional Council Unpublished report U98/24, Institute of Geological and Nuclear Sciences; Lower Hutt, New Zealand.

Brown, R.J: 1961:Hydrology of tritium in the Ottawa Valley Geochemica *et Cosmochimica Acta 21*:199-216

Browne, G.H. Field, B.D. 1985: The lithostratigraphy of Late Cretaceous to Early Pleistocene rock of Northern Canterbury, New Zealand, *New Zealand Geological Survey Record 6*, 63

Bouwer, H. 1978: *Groundwater Hydrology,* McGraw Hill Book Company, New York, 480p.

Campbell, J.K., Yousif, H.S. 1987: Tectonic Geomorphology of the Lower Waipara Gorge, North Canterbury, in "Field Trip Guides: Geological Society of New Zealand and New Zealand

Campbell, J.K. Nicol, A. 1992: Holocene folding and rupture on the Boby's Creek Fault and related Quaternary deformation along the Waipara River, in 'Field Trip Guides: Geological Society of New Zealand and New Zealand Geophysical Society Joint Conference' edited by J.K Campbell, *Miscellaneous Publication 63B*:137-153, Geological Society of New Zealand, Christchurch.

Campbell, J.K., Bennett, D., Brand, R., 2000: *Actively Emergent, Fault-Related Fold Structures Beneath the Canterbury Plains,* 2000 New Zealand Petroleum Conference, Unpublished Pre-Conference Field Trip Guide. University of Canterbury and Indo-Pacific Energy, Ltd., 12p.

Canterbury Regional Council, 1993: *Issues and Options for the Management of Water Resources in the Waipara Region.* Canterbury Regional Council Report 93(7)

Canterbury Regional Council, 1995: *But can I drink the water from my well? A guide for groundwater quality testing.* Published booklet R95(10), Christchurch, New Zealand.

Canterbury Regional Council, 1996: *Preliminary Assessment of Stream Depletion Effects from Groundwater Abstractions in the Waipara River Catchment.* Prepared for the CRC by Pattle Delamore Partners, Ltd., Canterbury regional Council Report U96/53

Canterbury Regional Council, 1998: *Well Database Manual.* Unpublished Technical Report U98/71, Canterbury Regional Council, Christchurch.

Chebotrarev, I. I. 1955: Metamorphism of natural waters on the crust of weathering. *Geochimica et Cosmochimica Acta 8,*

Clarke, I.D. Fritz, P. 1997: *Environmental isotopes in hydrogeology.* Lewis Publishers, Boca Raton, Florida, 328p.

Collins, B. W. 1939: *The geology of the Eastern Omihi District.* M.Sc. Thesis, University of New Zealand, deposited in the University of Canterbury Library, Christchurch New Zealand.

Department of Lands and Survey. 1976: *Canterbury Land District Coastal Reserves Investigation: Waipara County.* Unpublished report, 50p.

Dobrin, M.B., Savit, C.H., 1988: Introduction *to Geophysical Prospecting (fourth edition).* McGraw-Hill, New York.

Domenico, P.A. Schwartz, F.W. 1990: *Physical and chemical hydrogeology.* John Wiley and Sons, New York, 506p.

Driscoll, F.G. 1986: *Groundwater and wells* 2nd Ed, Johnson Filtration Systems Inc, St Paul, Minnesota.

Earl, P.L. 1998: *Springs Database Manual.* Canterbury Regional Council unpublished report U98/8, Christchurch.

Eriksson, E. 1958: The possible use of tritium for estimating groundwater storage, *Tellus 10*: 472-478.

Ekwurzel, B., Schlosser, P., Smethie, W.M., Jr., Plummer, L.N., Busenburg, E., Michel, R.L., Weppernig, R., and Stute., M. 1994: Dating of shallow groundwater: Comparison of the transient tracers $^3H/^3He$, chloroflurocarbons and $^{85}Kr$. *Water Resources Research, v. 30,* No. 6, 1693-1708.

Fetter, C.W. 1994: *Applied hydrogeology.* 3rd Ed., Prentice Hall, New Jersey.

Field, G. M. 1999: *Test of a buried sea cliff model using geophysical survey methods, Canterbury Plains, New Zealand.* B.Sc (Hons) University of Canterbury, Christchurch, New Zealand. 88p.

Fitterman, D.V. Stewart, M.D. 1986: Transient electromagnetic sounding for groundwater, *Geophysics 51(4)*: 995-1005.

Fitterman, D.V. 1987: Transient electromagnetic sounding in the Michigan Basin for ground water evaluation, *Ground Water 25:* 685-692.

Freeze, R.A. Cherry, J.A. 1979: *Groundwater.* Prentice-Hall, New Jersey.

Gage, D. R. 1950: *The geology of the Lower Waipara Gorge District.* M.Sc. Thesis, University of New Zealand, deposited in the University of Canterbury Library, Christchurch, New Zealand.

Gregg, D.R. 1959: Stratigraphy of the Lower Waipara Gorge, North Canterbury. *New Zealand Journal of Geology and Geophysics 2:501-527.*

Gregg, D.R. 1964: Sheet 18 – Hurunui. Geological map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington, New Zealand.

Hammer, S., Nettelton, L.L. and Hastings, W.K., 1945: Gravimeter prospecting for chromite in Cuba. *Geophysics,* vol. 10: 34-39.

Harris, M. G. 1983: *Canterbury Gravels, Omihi Stream section, Waipara.* M.Sc. Thesis, University of Otago, Dunedin, New Zealand.

Hem, J.D. 1992: *Study and Interpretation of the Chemical Characteristics of Natural Water.* 3rd Ed., US Geological Survey Water-Supply Paper 2254.

Horrell, G. 1992: *Water resources of the Waipara, Kowai and Motunau catchments.* Canterbury Regional Council unpublished report 14p.

Jobberns, G. King, L.C. 1927: The Canterbury Plains: their origin and structure. in, *The natural history of Canterbury,* edited by R Speight, A. Wall and R.M Laing, Philosophical Institute of Canterbury, Christchurch, New Zealand.

Jobberns, G. 1937: The Lower Waipara Gorge. *Transactions of the Royal Society of New Zealand 67(2):*125-132.

Kaufman, S. Libby, W.F. 1954. The natural distribution of tritium, *Physical Review 93*: 1337-1344.

Kearey, P. and Brooks, M. 1984: *An Introduction to Geophysical Exploration,* Oxford, Blackwell Scientific Publishing, 296p.

Kearey , P and Brooks, M. 1991 :*An Introduction to Geophysical Exploration,* 2nd edition, Blackwell Scientific Publications, 254p.

Kruseman, G.P. de Ridder, N.A.1990: *Analysis and evaluation of Pumping Test Data.* 2nd Ed. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Lloyd, J.W. Heathcote, J.A. 1985: *Natural inorganic hydrochemistry in relation to groundwater. An introduction.* Clarendon Press, Oxford.

Mason, B.H. 1941: The Geology of the Mt Grey District, North Canterbury. *Transactions of the Royal Society of New Zealand. 71(2): 103-27.*

McKay, A. 1892: On the Geology of the Middle Waipara and Weka Pass Districts, North Canterbury. *New Zealand Geological Survey Report of Geological Exploration 1890-91, 21: 97-103.*

McNeill, J.D. 1990: Use of electromagnetic methods for groundwater studies, in *Geotechnical and Environmental Geophysics* Volume 1-3, (ed. S.H. Ward), Oklahoma, Society of Exploration Geophysicists.

Milsom, J. 1989: *Field Geophysics,* New York, John Wiley Sons, 192pp.

Nicol, A. 1991: *Structural styles and kinematics of deformation on the edge of the New Zealand plate boundary zone, Mid-Waipara Region, North Canterbury.* M.Sc. Thesis, University of Canterbury, Christchurch, New Zealand.

Nicol, A. 1991: Haumurian (c. 66-80Ma) half-graben development and deformation, mid Waipara, North Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics,* 36: 127-130.

Nicol, A. Alloway, B. and Tonkin, P. 1994: Rates of deformation, uplift and landscape development associated with active folding in the Waipara area of North Canterbury, New Zealand. *Tectonics 13*: 1327-1344.

National Institute of Water and Atmospheric Research Ltd. 1996: *Stream Gauging,* Unpublished course notes for Canterbury Regional Council, National Institute of Water and Atmospheric Research Ltd.

Nobes, D.C. 1997a. *Chapter Four, Electrical and Electromagnetic Methods;* Unpublished geophysics lecture notes; Department of Geological Sciences, University of Canterbury, Christchurch.

Nobes, D.C. 1999: *Analysis of Proposals Submitted for Survey and Development of Groundwater Resources in the Waipara Area of North Canterbury.* Unpublished Technical Report U99/15, Canterbury Regional Council, Christchurch.

Ouchi, S. 1985: Response of alluvial rivers to slow active tectonic movement. *Geological Society of America Bulletin 96*: 504-515.

Parasnis, D.S. 1986: *Principles of Applied Geophysics.* Chapman & Hall, London.

Pattle Delamore Partners Ltd. 1996: *Preliminary assessment of stream depletion effects from groundwater abstractions it the Waipara River Catchment.* Unpublished Technical Report U96/53, Canterbury Regional Council, Christchurch.

Pettinga, J.R. Armstrong, M.J. 1998: North Canterbury active tectonics and earthquake hazards. *Geological Society of New Zealand Miscellaneous Publication* 101B.

Piper, A. M. 1944: A graphic procedure in the geochemical interpretation of water analyses. *Transactions, American Geophysical Union,* Vol 25, 914-923 pp.

Reilly, T.E. Plummer, L.N. Phillips, P.J. and Busenberg, E. 1994: The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resources Research 30*: 421-433.

Rhoades, J. D. 1985: Quality of Water for Irrigation, *Soil Science No. 113,* 277-284pp.

Robertson, W. A. 1991: N33 Culverden (1$^{st}$ Ed) Topographic Map 260, 1:50 000. Land Information New Zealand, Wellington, New Zealand.

Robertson, W.A. 1991: N34 Motunau (1st Ed) Topographic Map 260, 1: 50 000. Land Information New Zealand, Wellington, New Zealand.

Schlosser, P. Stute, M. Sonntag, C. and Munnich, K.O. 1989: Tritogenic $^{3}H$ in shallow groundwater, *Earth and Planetary Science Letters* 94: 245-254.

Speight, R. 1908: Some aspects of the terrace development in the valleys of the Canterbury Rivers, *Transactions of the New Zealand Institute 40*: 16-43.

Speight, R. 1915: The Intermontane Basins of Canterbury, *Transactions of the New Zealand Institute 47:336-53.*

Speight, R. 1919: The older gravels of North Canterbury. *Transactions of the New Zealand Institute,51*: 269-281.

Speight, R. Wall, A. and Laing, R.M (eds). 1927: *The natural history of Canterbury.* Philosophical Institute of Canterbury, Christchurch, New Zealand.

Stewart, M.K. Taylor, C.B. 1981: Environmental isotopes in New Zealand hydrology: 1. Introduction: The role of oxygen-18, deuterium, and tritium and hydrology. *New Zealand Journal of Science 24*: 295-311

Suggate, R.P. 1965: Late Pleistocene Geology of the Northern Part of the South Island, New Zealand. *New Zealand Geological Survey Bulletin 77.*

Taylor, C.B. Wilson, D.D. Brown, L.J. Stewart, M.K. Burden, R.J. and Brailsford, G.W. 1989: Sources and flow of North Canterbury Plains groundwater, New Zealand. *Journal of Hydrology 106*:311-340.

Telford, W.M. Geldhart, L.P and Sheriff, R.E. 1990: *Applied Geophysics 2nd Edition,* Cambridge University Press: London, England.

Thompson, J. A. 1920: The Neotocene Geology of the Middle Waipara and Weka Pass District, North Canterbury, New Zealand. *Transactions of the New Zealand Institute 52: 322-415*

Thompson, G.M., Hayes, J.M. and Davis, S.N. Davis. 1974. Fluorocarbon tracers in hydrology. *Geophysical Research Letters 1: 177-80.*

Tonkin, P.J. Alloway, B. and Nicol, A. 1992: Landuse, soils and tectonic geomorphology of the Waipara and Omihi Valleys, North Canterbury, *Geological Society of New Zealand Miscellaneous Publication* 63B.

Vinogradov, A.P. Devirts, A.L. and Dobkina, E.I. 1968: The current tritium contents of natural waters. *In: Y. Kitano (ed), Geochemistry of Water,* Benchmark Papers in Geology, Vol.16, Dowden, Hutchinson & Ross, Inc., Stroudsburg, PA.

Whiteford, C. M. 1978: Sheet 18, Hurunui (1st Ed) Gravity Map of New Zealand, 1:250 000. Department of Scientific and Industrial Research, Wellington, New Zealand.

Wilson, D.D. 1955: The northern continuation of the Canterbury plains, Canterbury, New Zealand. *New Zealand Journal of Science and Technology 37*: 126-131.

Wilson, D.D. 1963: The Geology of the Waipara Subdivision (Amberley and Motunau Sheets S68 and S69). *New Zealand Geological Survey Bulletin 64*, 122p.

Wilson, D.D. 1973: The significance of geology in some current water resource problems, Canterbury Plains, New Zealand. *Journal of Hydrology (N.Z) 12(2)*:103-118.

Wilson, D.D. 1983: *Glenmark Irrigation Scheme Hydrogeological Study.* Unpublished Report. Ministry of Works, 36p.

Wilson, D.D. 1985: Erosional and depositional trends in rivers of the Canterbury Plains, New Zealand. *Journal of Hydrology (N.Z) 24(1)*: 32-44.

Yousif, H. M. S. 1987: *The Application of remote sensing to geomorpological neotectonic mapping in North Canterbury,* PhD. Thesis, University of Canterbury, Canterbury, New Zealand.

## GLOSSARY of TERMS

**Alluvium** Sediments deposited by flowing rivers. Depending upon the location in the floodplain of the river, different-sized sediments are deposited.

**Anisotropy** The condition under which one or more of the hydraulic properties of an acquifer vary according to the direction of flow.

**Aquiclude** A low-permeability unit that forms either the upper or lower boundary of a ground-water flow system.

**Aquifer** Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic qualities of water to wells and springs.

**Aquifer, confined** An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer.

**Aquifer, perched** A region in the unsaturated zone where the soil may be locally saturated because it overlies a low-permeability unit.

**Aquifer, semi-confined** An aquifer confined by a low-permeability layer that permits water to slowly flow through it. During pumping of the acquifer, recharge to the aquifer can occur across the confining layer. Also known as a leaky artesian or leaky confined aquifer.

**Aquifer, unconfined** An aquifer in which there are no confining beds between the zone of saturation and the surface. There will be a water table in an unconfined aquifer. Water-table aquifer is a synonym.

**Aquifuge** An absolutely impermeable unit that will neither store nor transmit water.

**Aquitard** A low-permeability unit that can store ground water and also transmit it slowly from one aquifer to another.

**Artificial recharge** The process by which water can be injected or added to an aquifer. Dug basins, drilled wells, or simply the spread of water across the land surface are all means of artificial recharge.

**Barrier boundary** An aquifer-system boundary represented by a rock mass that is not a source of water.

**Baseflow** That part of stream discharge from ground water seeping into the stream.

**Cation-exchange capacity** The ability of a particular rock or soil to absorb cations.

**Confining layer** A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.

**Connate water** Interstitial water that was not buried with a rock but that has been out of contact with the atmosphere for an appreciable part of a geologic period.

**Diffusion** The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

**Direct precipitation** Water that falls directly into a lake or stream without passing through any land phase of the runoff cycle.

**Discharge** The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.

**Discharge area** An area in which there are upward components of hydraulic head in the aquifer. Ground water is flowing toward the surface in a discharge area and may escape as a spring, seep, or baseflow or by evaporation and transpiration.

**Dispersion** The phenomenon by which a solute in flowing ground water is mixed with uncontaminated water and becomes reduced in concentration. Dispersion is caused by both differences in the velocity that the water travels at the pore level and differences in the rate at which water travels through different strata in the flow path.

**Drawdown** A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells.

**Electrical sounding** An earth-resistivity survey made at the same location by putting the electrodes progressively farther apart. It shows the change of apparent resistivity with depth.

**Electromagnetic conductivity** A method of measuring the induced electrical field in the earth to determine the ability of the earth to conduct electricity. Electromagnetic conductivity is the inverse of electrical resistivity. Also known as electric conductivity and terrain conductivity.

**Equipotential line** A line in a two-dimensional ground-water flow field such that the total hydraulic head is the same for all points along the line.

**Equipotential surface** A surface in a three-dimensional ground-water flow field such that the total hydraulic head is the same everywhere on the surface.

**Equivalent weight** The formula weight of a dissolved ionic species divided by the electrical charge. Also known as combining weight.

**Evaporation** The process by which water passes from the liquid to the vapour state.

**Evapotranspiration** The sum of evaporation plus transpiration.

**Evapotranspiration, actual** The evapotranspiration that actually occurs under given climatic and soil-moisture conditions.

**Evapotranspiration, potential** The evapotranspiration that would occur under given climatic conditions if there were unlimited soil moisture.

**Flow, steady** The flow that occurs when, at any point in the flow field, the magnitude and direction of the specific discharge are constant in time.

**Flow, unsteady** The flow that occurs when, at any point in the flow field, the magnitude or direction of the specific discharge changes with time. Also called transient flow or nonsteady flow.

**Ground water** The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer.

**Ground-water basin** A rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighbouring ground-water reservoirs. A ground-water basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

**Ground water, confined** The water contained in a confined aquifer. Pore-water pressure is greater than atmospheric at the top of the confined aquifer.

**Groundwater flow** The movement of water through openings in sediment and rock; occurs in the zone of saturation.

**Groundwater, perched** The water in an isolated, saturated zone located in the zone of aeration. It is the result of the presence of a layer of material of low hydraulic conductivity, called a perching bed. Perched ground water will have a perched water table.

**Hantush-Jacob formula** An equation to describe the change of hydraulic head with time during pumping of a leaky confined aquifer.

**Head, total hydraulic** The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.

**Heterogeneous** Pertaining to a substance having different characteristics in different locations. A synonym is nonuniform.

**Homogeneous** Pertaining to a substance having identical characteristics everywhere. A synonym is uniform.

**Hydraulic conductivity** A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

**Hydraulic gradient** The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

**Hydrochemical facies** Bodies of water with separate but distinct chemical compositions contained in an aquifer.

**Hydrogeology** The study of the interrelationships of geologic materials and processes with water, especially ground water.

**Hydrograph** A graph that shows some property of ground water or surface water as a function of time.

**Hydrologic equation** An expression of the law of mass conservation for purposes of water budgets. It may be stated as inflow equals outflow plus or minus changes in storage.

**Image well** An imaginary well that can be used to simulate the effect of a hydrologic barrier, such as a recharge boundary or a barrier boundary, on the hydraulics of a pumping or recharge well.

**Interflow** The lateral movement of water in the unsaturated zone during and immediately after a precipitation event. The water moving as interflow discharges directly into a stream or lake.

**Intrinsic permeability** Pertaining to the relative ease with which a porous medium can transmit liquid under a hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field.

**Ion exchange** A process by which an ion in a mineral lattice is replaced by another ion that was present in an aqueous solution.

**Isotropy** The condition in which hydraulic properties of the aquifer are equal in all directions.

**Jacob straight-line method** A graphical method using semilogarithmic paper and the Theis equation for evaluating the results of a pumping test.

**Karst** The type of geologic terrane underlain by carbonate rocks where significant solution of the rock has occurred due to flowing ground water.

**Laminar flow** The type of flow in which the fluid particles follow paths that are smooth, straight, and parallel to the channel walls. In laminar flow, the viscosity of the fluid damps out turbulent motion. *Compare with* turbulent flow.

**Leaky confining layer** A low-permeability layer that can transmit water at sufficient rates to furnish some recharge to a well pumping from an underlying aquifer. Also called aquitard.

**Lithologic log** A record of the lithology of the rock and soil encountered in a borehole from the surface to the bottom. Also known as a well log.

**Micrograms per litre** A measure of the amount of dissolved solids in a solution in terms of micrograms of solute per litre of solution.

**Milliequivalents per litre** A measure of the concentration of a solute in solution; obtained by dividing the concentration in milligrams per litre by equivalent weight of the ion.

**Milligrams per litre** A measure of the amount of dissolved solids in a solute in terms of milligrams of solute per litre of solution.

**Observation well** A nonpumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer.

**Piezometer** A nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.

**Porosity** The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

**Potentiometric surface** A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

**Potentiometric surface map** A contour map of the potentiometric surface of a particular hydrogeologic unit.

**Pumping cone** The area around a discharging well where the hydraulic head in the aquifer has been lowered by pumping. Also called cone of depression.

**Pumping test** A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called aquifer test.

**Recharge area** An area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area.

**Recharge basin** A basin or pit excavated to provide a means of allowing water to soak into the ground at rates exceeding those that would occur naturally.

**Recharge boundary** An aquifer system boundary that adds water to the aquifer. Streams and lakes are typically recharge boundaries.

**Recharge well** A well specifically designed so that water can be pumped into an aquifer in order to recharge the ground-water reservoir.

**Recovery** The rate at which the water level in a well rises after the pump has been shut off. It is the inverse of drawdown.

**Runoff** The total amount of water flowing in a stream. It includes overland flow, return flow, interflow, and baseflow.

**Safe yield** The amount of naturally occurring ground-water that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native ground-water quality or creating an undersirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head caused by pumping.

**Saturated zone** The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

**Specific capacity** An expression of the productivity of a well, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well. Specific capacity should be described on the basis of the number of hours of pumping prior to the time the drawdown measurement is made. It will generally decrease with time as the drawndown increases.

**Specific discharge** An apparent velocity calculated from Darcy's law; represents the flow rate at which water would flow in an aquifer if the aquifer were an open conduit.

**Specific yield** The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Gravity drainage may take many months to occur.

**Stiff pattern** A graphical means of presenting the chemical analysis of the major cations and anions of a water sample.

**Storativity** The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called storage coefficient.

**Stream, gaining** A stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an elluent stream.

**Stream, losing** A stream or reach of a stream that is losing water by seepage into the ground. Also known as an influent stream.

**Throughflow** The lateral movement of water in an unsaturated zone during and immediately after a precipitation event. The water from throughflow seeps out at the base of slopes and then flows across the ground surface as return flow, ultimately reaching a stream or lake.

**Transmissivity** The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

**Unsaturated zone** The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. the pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched ground water, may exist in the unsaturated zone. Also called zone of aeration and vadose zone.

**Water budget** An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin.

**Water table** The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells.

**Water-table map** A specific type of potentiometric-surface map for an unconfined aquifer; shows lines of equal elevation of the water table.

**Well development** The process whereby a well is pumped or surged to remove any fine material that may be blocking the well screen or the aquifer outside the well screen.

**Well, fully penetrating** A well drilled to the bottom of an aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer.

**Well, partially penetrating** A well constructed in such a way that it draws water directly from a fractional part of the total thickness of the aquifer. The fractional part may be located at the top or the bottom or anywhere in between in the aquifer.

**Well screen** A tubular device with either slots, holes, gauze, or continuous-wire wrap; used at the end of a well casing to complete a well. The water enters the well through the well screen.

**Wenner array** A particular arrangement of electrodes used to measure surface electrical resistivity